Tyndall°Centre
for Climate Change Research

A blueprint for the integrated assessment of climate change in cities

Richard Dawson, Jim Hall, Stuart Barr, Mike Batty,
Abigail Bristow, Sebastian Carney, Stephen Evans,
Alistair Ford, Jonathan Köhler, Miles Tight and Claire Walsh.

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A blueprint for the integrated assessment of climate change in cities

Tyndall Centre for Climate Change Research Cities Research Programme

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Executive Summary

Tyndall Cities Programme

The aim of the Tyndall Centre Cities Programme is to develop a city-scale assessment capacity that simulates the evolution of climate impacts and emissions over the 21st century. This city-scale assessment tool will be applied for urban policy-makers, planners, engineers and other stakeholders to compare alternative adaptation and mitigation strategies and to consider *how cities grow whilst reducing emissions and vulnerability to climate change*.

Climate change and cities

The high density of people and economic activity makes cities potential concentrations of climate vulnerability. Potential climate impacts can have a direct impact on the city such as flooding, drought, heatwaves *etc*. whilst others, such as changes to available agricultural resources are less direct. Meanwhile, cities are also major emitters of greenhouse gases both directly (*eg*. heating, electricity use) and indirectly (*eg*. embedded carbon in manufactured and agricultural goods). Adaptation to climate change can often induce energy-intensive adaptations, such as air conditioning or desalinisation, that undermine emissions reduction efforts.

The Urban Integrated Assessment Framework (UIAF) being developed for the Tyndall Cities programme is unique in that it:

- integrates quantitative evaluations of climate impacts and emissions at an urban scale,
- is driven by internally consistent scenarios of global climate and socio-economic change over the 21st century,
- explores the interaction between land use, climate impacts and emissions,
- involves the analysis of both adaptation and mitigation options in a unified framework., and,
- enables uncertainties in climate change analysis to be considered.

London

The first case study of the UIAF is in London. London is the capital city of the United Kingdom and provides an interesting and challenging case study site for this implementation of a city-scale analysis because it:

- is the most populous city in the European Union although has a relatively low population density,
- has a strong and diverse economy (in particular tourism and the financial services industry),

- has an elected mayor who has a climate change remit,
- has already implemented significant climate adaptation and mitigation policies,
- has a diverse and unique public transport system amongst British cities,
- is made up of over 30% greenspace,
- contributes to over 6% of the UK's CO_2 and significant amounts of other greenhouse gases, and,
- is vulnerable to flooding, water shortages and heatwaves and other climate impacts.

Climate policy questions

A number of climate related policy questions and priorities have been identified after a literature review and meeting with a number of stakeholders, those which may realistically be addressed in this research programme include:

- Exploring the effectiveness of:
    - economic instruments such as taxation and emissions trading,
    - development and land use regulation,
    - transport regulation and emissions charging,
    - increasing energy efficiency through retrofitting buildings or deploying improved technology, and,
    - infrastructure projects such as new reservoirs, raised flood defences *etc.*
- Attributing risk between climate change and vulnerability,
- Identifying planning policy that can reduce climate impacts and emissions,
- Identifying adaptation and mitigation strategies that are robust to climate change uncertainties,
- Exploring the importance of cumulative effects and sequencing of planning decisions on emissions reduction or risk.

Urban Integrated Assessment Framework

On the scale of large cities it is meaningful to think about climate impacts, adaptation and mitigation in the same quantified assessment framework. This is a scale at which strategies for mitigation and adaptation can be usefully designed and assessed. Yet urban climate mitigation and adaptation policy and behaviour can hardly be divorced from its global context. The framework for integrated assessment, shown in Figure 1, therefore is driven by internally consistent global and national scenarios of climate and socio-economic change. These boundary conditions drive scenarios of regional economy and land use change, ensuring that whilst they are influenced by local policy, these scenarios are also globally consistent. It is at the level of land use modelling that the analysis becomes spatially explicit. Scenarios of land use and city-scale climate and socio-economic change inform the emissions accounting and climate impacts modules. The final component of the framework is the integrated assessment tool that provides the interface between the modelling components, the results and the end-user. This tool will enable a number of adaptation and mitigation options to be explored within a common framework.

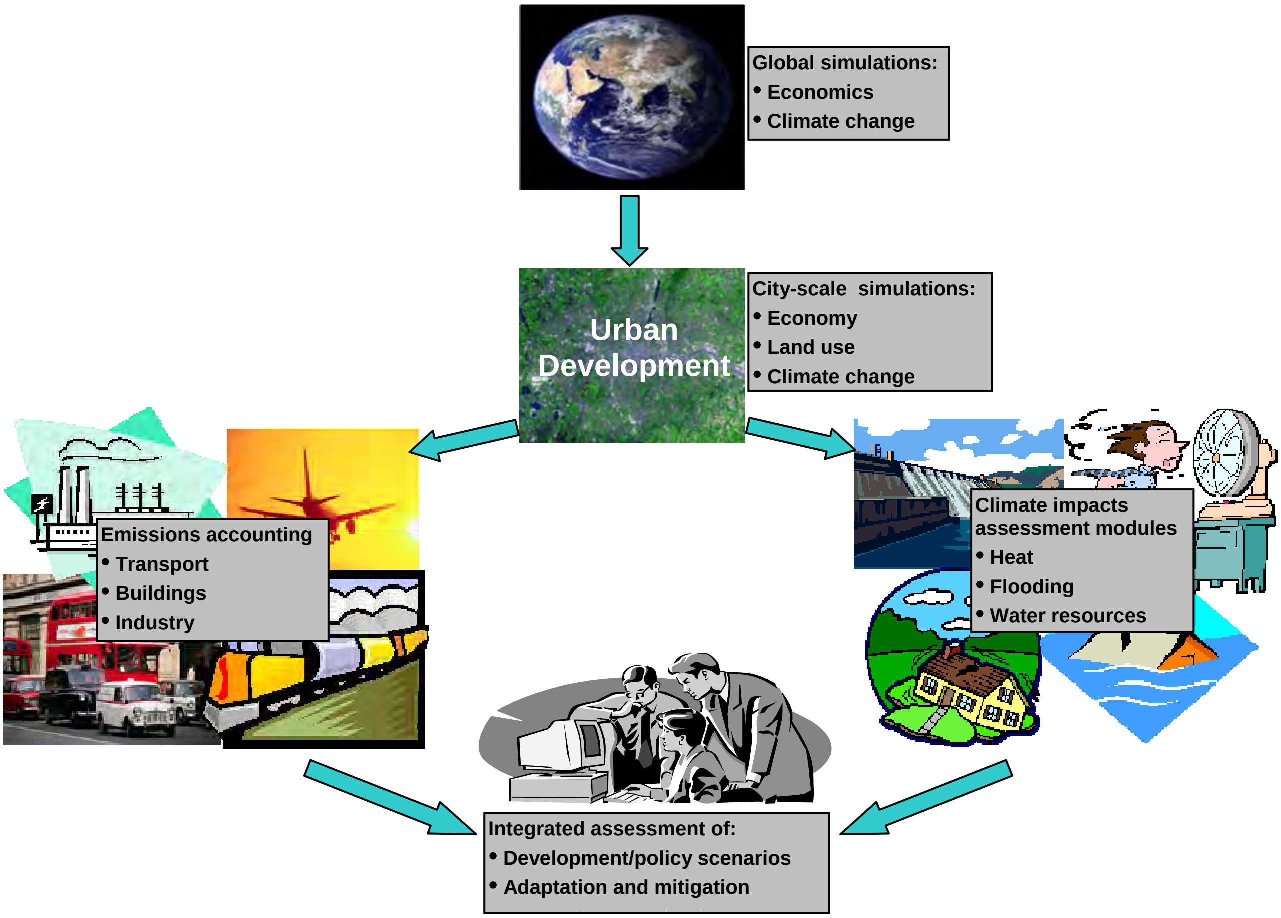

Figure 1 Overview of Urban Integrated Assessment Framework (UIAF)

Workplan

The timescale of the Cities programme is 3 years in total. The first six months or so have been a review which led to the first version of this working paper. The programme finishes in Spring 2009 and will be marked by a stakeholder 'launch event'. The main phases of the research programme are to:

1) Perform a preliminary scoping review (this report),
2) Develop the component models of economics, land use, transport and emissions accounting and climate impacts assessment,
3) Implement a preliminary demonstration of the UIAF that shows the impact on landuse and flood risk of a limited number of global and urban socio-economic scenarios,
4) Develop the UIAF by integrating the climate impacts and emissions accounting models,
5) Design, with stakeholders, and test portfolios of adaptation and mitigation options,

6) Write up findings in papers and a consolidated report for stakeholders and hold a stakeholder launch event.

Limitations and further work

A number of limitations of the current UIAF have been recognised. Future research and development needed to address these, and other related issues are:

- Additional impacts assessment modules (*eg.* windstorm or subsidence)
- Analysis of broader urban footprint issues and embedded energy and emissions,
- Simulation-based modelling of feedbacks between climate impacts, transport, landuse change and economy,
- How urban areas can be better represented in Earth Systems Modelling, and,
- Issues likely to arise from implementing a similar UIAF in other cities – in particular cities undergoing rapid change or with scarce data.

This version of this report should be referenced as:

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Chapter 1 Introduction and overview

1.1 *Objectives*

The objectives of this report are to:

1) Introduce the Tyndall Centre Cities Programme and outline its aims and objectives.
2) Review the key impacts on cities from global and climatic change and how comparable and related projects have attempted to address these issues.
3) Report on the findings of the stakeholder review of key policy issues for London.
4) Describe the city-scale integrated assessment framework both in generic terms to demonstrate how the approach may be transferred between cities and in detail describing exactly how it is being implemented for London.
5) Identify areas for future development.

Chapter 1 of this report provides an introduction to the challenges facing cities and the Tyndall Centre for Climate Change Research Cities Programme. Chapter 2 provides an introduction to London, the case study site for the Tyndall Centre study and overview of the challenges facing London and a review of the issues concerning stakeholders in London. Chapter 3 introduces the framework for integrated urban climate impacts assessment. This framework is supplemented by further technical details in the Appendices. Chapter 4 outlines the timescale for the Tyndall project and identifies key deliverables. The full work plan is given in the Appendices. Chapter 5 identifies areas for further work, and a summary of the report is provided in Chapter 6.

1.2 *The Tyndall Centre Cities Programme*

The Tyndall Centre is multi-disciplinary research centre that brings together scientists, economists, engineers and social scientists from a range of institutions to address the substantial challenges posed by global and environmental change. The Tyndall Centre actively engages with business leaders, policy advisors, the media and the public to explore sustainable solutions to climate change at the: local, regional, national and international level.

The rationale behind the Cities programme is that:

- Urban areas are potential concentrations of climate vulnerability as well as being greenhouse gas emitters,
- Urban areas need to be studied in the context of national and global socio-economic and climate changes, and,

- Innovative approaches to adaptation and mitigation can be developed by *integrated assessment* of urban systems.

Work on the cities programme began in April 2006. It is anticipated that working assessment methods will be available in mid to late 2007. The project will be complete in March 2009. The programme seeks to develop a city-scale assessment capacity that simulates the evolution of climate impacts and emissions over the 21st century and can be applied by urban policy-makers, planners, engineers and other stakeholder to design, simulate, evaluate and compare alternative adaptation and mitigation strategies to allow them to address the question:

"*How do cities grow whilst reducing emissions and vulnerability to climate impacts?*"

This will be achieved by addressing the following key objectives:

- Design a blueprint for an integrated urban assessment framework.
- Develop and demonstrate a downscaling methodology for generating scenarios of urban economic indicators and spatial attributes that are consistent with variables in coupled global economic and climate simulations.
- Develop and demonstrate a city-scale greenhouse gas emissions accounting tool.
- Adapt and apply methods for city-scale climate impacts assessment.
- Evaluate, in city-scale assessments, strategies and technologies for reducing climate impacts and greenhouse gas emissions.

This report is the culmination of the first objective.

1.3 *Cities on the front line*

1.3.1 Urbanisation

Urbanisation is one of the most powerful and visible anthropogenic forces on Earth. Over the 20th century it resulted in humans shifting from being a rural to an urban species and is expected to continue over the 21st century. Urbanisation is driven by social processes that result in an increase over time in the population and/or extent of cities and towns. These drivers may include changes to: population, employment opportunities associated with industrialisation, consumption patterns, international migration and accessibility.

Cities occupy less than 3 percent of the Earth's land surface (Balk *et al.*, 2004) but now house just over 50 per cent of the world's population, a figure that was only 14% in 1900 (Douglas, 1994) and is estimated to increase to 60 per cent by 2030 (UN 2004a, UN 2004b). The rate of growth in developing countries is faster than in industrialised nations: for example in 1978, 17.9% of China's population was living in cities, yet by 2003 39% of its 1.3billion population lived in urban areas (Zhao *et al.*, 2006). Currently there are 19 mega-cities (>10 million people); 22 cities with 5-10million people; 370 cities with 1-5million people and 433 cities with 0.5-1million people worldwide (UNCHS 2002, Kraas 2003, MunichRe 2004). Of the mega-cities, the majority are situated in developing countries and the coastal zone (Nicholls, 1995). However, it is the medium sized cities that are growing most rapidly (Montgomery *et al.*, 2004).

The most prominent visual features of urbanisation are the buildings and infrastructure. However, the influence of urbanisation extends far beyond the palpable terraforming that occurs within urban boundaries. Resources consumed by city dwellers generate an 'urban footprint': land use changes and resource movements between other rural and urban areas that extend far beyond the physical or political urban boundaries. Urban activities release greenhouse gases directly (*eg.* from petrol-based transport), and indirectly (*eg.* through electricity use and consumption of industrial and agricultural products). Furthermore, a high density of people makes them possible focal points of vulnerability to climate change. Conversely, they also represent concentrated opportunities for adaptation to climate impacts and mitigation of greenhouse gas emissions.

It is evident therefore that urbanisation is both an outcome and driver of global and environmental change through the interaction of cities with the Earth System. It should be noted that the background provided in this and the following sub-sections reviews issues most salient to this research, and whilst other issues may be touched upon this report, is not intended to provide a comprehensive review of the interactions between urbanisation and global environmental change.

1.3.2 The impacts of climate change on urban areas

Due to their high concentration of people, business, infrastructure and industry, cities inherently have potential to be hotspots of climate change impacts. Potential climate impacts on urban areas include (IPCC 2001b, DoH 2001, Hulme *et al.*, 2002):

- Sea level rise and storm surge flooding,
- Fluvial flooding,
- Urban drainage flooding,
- Building and infrastructure subsidence and landslides,
- Wind storm,
- Drought and implications for water resources both in terms of quality (and concomitant implications for health and aquatic ecosystems) and availability for human consumption, industry and neighbouring agricultural areas,

- Heat and health (changing profile of heat vs. cold related deaths),
- Air quality and health,
- Resources and amenity (including agriculture, fisheries, waste management, ecology, wildlife, biodiversity and fires), and,
- Disease (changing profile of vector and water-borne diseases).

Evidently, some of these impacts directly interact with the urban area (eg. floods), whilst others are indirect (eg. changes to agricultural resources). Likewise, some of the impacts are more readily estimated (eg. properties damaged in a flood) than others (eg. marginal changes in vector-borne diseases). However, these climate impacts pose urgent and very real problems. In the 2003 summer heat wave there were at least 35,000 deaths in Europe, primarily in urban areas (Fink *et al.*, 2004). Development of flood prone areas of the Thames Gateway in London is not yet complying with the recommendations of the Environment Agency (2003) and the Association of British Insurers (2004). Eight UK water firms issued a hosepipe ban and several applied for a drought order in the summer of 2006. Despite some high profile flooding events in the last two decades, more people have died from windstorm and since 1950 windstorms have been responsible for almost three-quarters of the UK's insured losses (ABI, 2003) and are as significant in the rest of the world (MunichRe, 2004).

1.3.3 Vulnerability

Climate change on its own does not necessarily imply significant impacts. Furthermore, a high concentration of population and buildings does not necessarily correlate directly with high vulnerability. The vulnerability of urban areas to climate change is a function of social, economic and political processes. Proposed key factors include (Adger and Vincent, 2005, Allenby and Fink, 2005, Adger *et al.*, 2005):

- Economic well-being and stability (*eg.* standard of living; rate of urbanisation),
- Demographic structure of population,
- Institutional stability (*eg.* institutional 'memory'; corruption)
- Strength of and reliance on public infrastructure (*eg.* health expenditure; communication infrastructure; financial, transport, corporate and systems; degree of centralisation)
- Global interconnectivity (*eg.* trade balance; tourism), and,
- Natural resource dependence and regenerative ability of ecosystems.

Measures that can be undertaken to reduce vulnerability might include the diversification of ecological and economic systems and building inclusive governance structures; essentially taking a portfolio approach to minimising risks across society in the broadest sense. Evidently, a key aspect of this is a portfolio approach that involves combining diverse approaches ranging from institutional and governance issues to technological systems (such as communication networks) and civil infrastructure (*eg.* adaptable engineering in construction or refurbishing). The Tyndall Centre has contributed significantly to questions of vulnerability, adaptive capacity and social resilience in Phase I, and continues to do so in Research Programme 3 of the Tyndall Centre Phase II. The purpose of the Cities Programme is not to advance generic thinking on these issues but rather to demonstrate how they can be played out in practical terms at the city scale.

1.3.4 Emissions

The main anthropogenic sources of greenhouse gas (GHG) emissions are (Marland *et al.*, 1999, Marland *et al.*, 2000, IPCC, 2001a):

- Fossil fuel burning & cement production (6.3±0.4GtC/year), and,
- Forest burning, soil disruption and land use change (1.6±1.0GtC/year)

Of the fossil fuel and cement production sources, the majority (91%) of global CO_2 emissions are related to energy production. In terms of CO_2 equivalence, CH_4 contributes 19% with other industrial emission (eg. N_2O, HFCs) making up the rest (IPCC, 2000). These emissions have implications for climate change both globally (*eg.* in terms of changing patterns of temperature and precipitation) and locally (*eg.* in terms of adverse health impacts, or local changes in temperature). Around 80% of the greenhouse gases that affect the climate are related to urban activity (MunichRe, 2004) and it is therefore appropriate to develop emissions accounting and mitigation strategies at this scale.

1.3.5 Adaptation and mitigation

At a city scale, there are a number of possible adaptation and mitigation options. However, if poorly managed, or not considered at a broad scale and with a view to long term consequences, climate impacts can induce energy-intensive adaptations such as air conditioning, pumped drainage or desalination. These energy-intensive adaptations can undermine efforts aimed at mitigating GHG emissions. Moreover, failure to consider a range of possible impacts over extended timescales can lead to undesirable 'lock-in' to specific adaptation options (Brewer and Stern, 2005). For example, construction of flood defence infrastructure can lead to intensive floodplain development that subsequently ties floodplain managers in to further flood defence infrastructure as alternatives such as managed retreat become prohibitively expensive (*c.f.* Kates, 1971, Wilde, 2001). Analysing urban *systems* with evidence-based assessment tools can help cities escape from the viscous circle of increasing climate impacts and emissions.

Mitigating and adapting to climate change in urban areas involves complex interactions of citizens, governmental/non-governmental organisations and businesses. This complexity can inhibit the development of integrated strategies (which may involve transportation demand management, land use planning and construction of new civil infrastructure) whose combined effect is more beneficial than the achievements of any single agency or organisation acting unilaterally. Adaptation and mitigation strategies need to be designed as adaptable portfolios of options

1.4 *Distinctiveness of Tyndall Cities Programme research*

There are a significant number of initiatives being undertaken to address the challenge of climate change in urban areas. A short review of major initiatives is given in Appendix A. Whilst this can never be a complete review it gives an indication of the breadth of current initiatives. Whilst there is evidently substantial ongoing research, development and policy related initiatives in urban areas it should be clear that the Tyndall Cities Programme is quite unique because it brings together *all* of the following features in an *integrated assessment* of urban areas:

- Quantitative evaluation of broad range of climate impacts and emissions sources.
- Driven by and consistent with scenarios of global climate and socio-economic change.
- Analysis is reported over a broad spatial scale relevant to urban policy makers.
- Analysis is reported over an extended timescale relevant to addressing climate change challenges.
- Explores the interaction between land use, impacts, emissions and climate change.
- Involves analysis of both adaptation and mitigation options.
- Construction of multi-sector portfolios of management options.
- Quantification of uncertainties.
- Analysis of the robustness of management options to uncertainties.
- Informed by stakeholder input.

Chapter 2 London and key policy issues

This chapter introduces London, the case study city of the Tyndall Centre Cities Programme. A background into the city and a summary of the main pressures that global climate and socio-economic change are expected to bring is provided. This is followed by a review of stakeholder issues in London.

2.1 *London*[*]*: A history and overview*

2.1.1 Background and demographics

London is the capital city of the United Kingdom and has been a settlement for around two millennia. It has a wide and diverse cultural, social, economic, environmental and built heritage and is one of the most culturally diverse cities in the world with 29 percent of the population from ethnic minorities, speaking almost 300 languages (ONS, 2001a, GOL, 2006a).

The population of London grew rapidly throughout the 19th and early 20th centuries and was the most populated city in the world from 1825-1925 when it was overtaken by New York. London is by some margin the most populous city in the European Union (Eurostat, 2005, ONS, 2001a). Compared to other world cities and most European capitals, London has a relatively low population density. The population of London was 8.6million in 1939, but declined over the following years to 6.7million in 1988, but has since climbed to 7.2million and is expected to be over 8.1million by 2016 (GLA, 2004). Within the UK there has been a net migration from London (mainly to the adjacent South East or East of England regions) except for the 16-24 age range, but these losses were matched by international migration to London (ONS, 2001b). The natural change in population (births minus deaths) is high compared to the rest of the UK due to its younger population resulting in more births and fewer deaths.

The average household size in London is 2.3 people, which is also the national average. However, over 1 millions properties have only a single occupancy, this equates to 5 percent more households than the rest of England and Wales. There are in excess of 3 million domestic properties in London, of which 16 percent are rented by the private sector, 26 percent are rented by local authorities or non-profit making social landlords and 58 percent are owner-occupied. This compares to the national average of

[*] In section 2.1, London is used to refer to the area governed by the Greater London Authority, unless stated otherwise.

10, 21 and 69 percent respectively (ODPM, 2004b). There has been a general decrease in the annual rate of housing construction from 23,200 in 1980 to 14,200 in 2001. However, the Greater London Authority set a minimum target of 23,000 additional homes each year (GLA, 2004).

A significant proportion of London's labour force are employed in high paying industries, often with additional allowances for working in the capital. Although a large percentage of these earners also live in the capital, many commute from outside. Regardless, 33 percent of London households are classed as high-income (>£750/week) compared to 20 percent for the rest of the nation. However, a higher proportion of individuals in London had average household incomes in the bottom fifth than in any other region in the UK (ONS, 2004a). Moreover, whilst London contains some of the least deprived boroughs, such as Richmond upon Thames which is ranked 300th out of 354, Hackney is ranked as the most deprived local authority in England (ODPM, 2004c).

2.1.2 Geography

London is situated on the river Thames which flows South West to East through the city. The city was founded on the North bank of the Thames close to the original London Bridge but the gentle topography of the surrounding area has allowed London to expand in an approximately circular manner. The river Thames has been narrowed over the past few centuries through embanking and reclamation.

Greater London consists of 33 boroughs or Local Administrative Units (LAUs) (Figure 2-1) and covers an area of 1,584km^2 making it one of the largest urban areas in the European Union (Eurostat, 2005). London is often further split into the City of London, Inner London and Outer London. The City of London is the 1 square mile (2.6km^2) that contains much of the UK's financial services industry. Inner London consists of 14 more central boroughs that are surrounded by Outer London (ONS, 2003). Using the European Union's Nomenclature of Units for Territorial Statistical (NUTS) classification, these can be further divided into five areas (Figure 2-1). London is bordered by two other English regions: East and South East (Figure 2-2). The Thames Gateway is a 40 mile tract of land that stretches from the London Docklands to the Thames Estuary. The Gateway has been targeted for significant development over the coming decades and will host the Olympics in 2012.

In terms of climate change mitigation, it is also useful to consider a further sub-division that is the congestion charging zone (toll imposed upon entering traffic), which consists of the whole of the city of London, large parts of the City of Westminster and parts of the surrounding boroughs. This is likely to expand in the future.

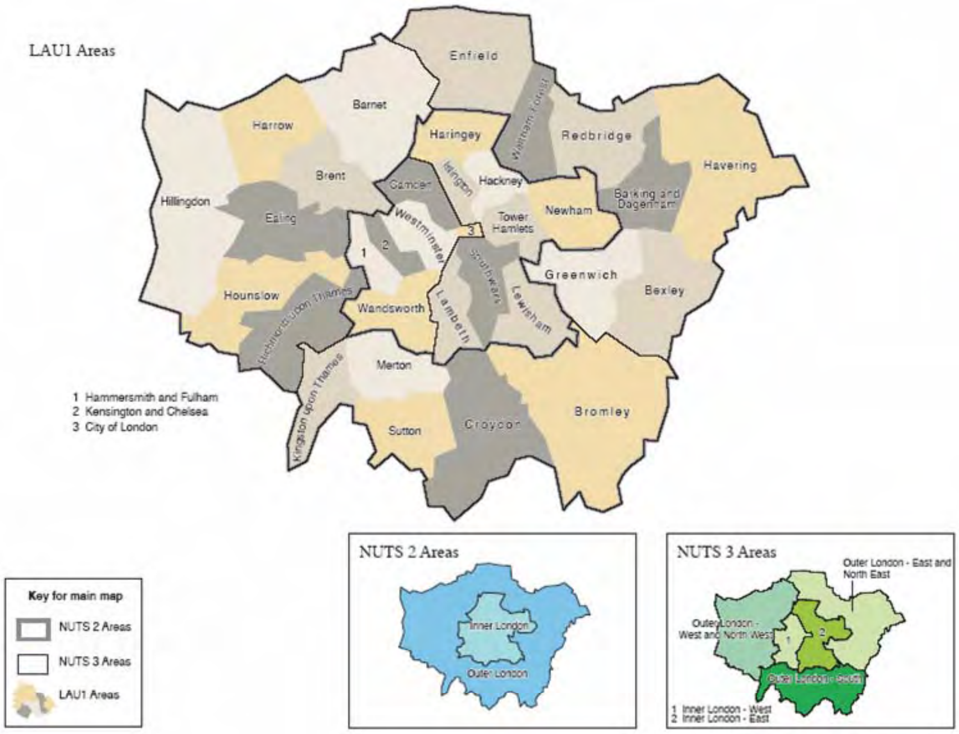

Figure 2-1 The geography of London and its boroughs (from ONS, 2001c)

Figure 2-2 English Government Office Regions (from ONS, 1998)

2.1.3 Governance

London governance is crowded and complex. For instance, improvement of a street environment in central environment may involve the relevant London borough, the Royal Parks Agency, the Central London Partnership and the Greater London Authority (Hunt, 2005). The organisations most relevant to the strategic city-scale management issues being considered in this work are now introduced.

The Greater London Authority (GLA) was established in 2000 and covers the 32 London boroughs and the Corporation of London (the municipal governing body of the City of London). It comprises a directly elected Mayor and a separately elected Assembly. The GLA is a public authority, designed to provide citywide, strategic government for London. The principal purpose of the GLA is to promote the economic and social development and the environmental improvement of Greater London. As part of this the GLA have developed a Spatial Development Strategy for London – called the London Plan – which is periodically reviewed. The London Plan and its relevance to this study is discussed in Section 2.2.2. The boroughs are responsible for local services such as local planning, schools, refuse *etc.* not overseen by the GLA. The London Development Agency (LDA) co-ordinates the GLA's economic development and regeneration plans. In addition to the LDA, the mayor has wide power of direction over Transport for London, which provides bus, river and some light rail services (but not mainline and commuter rail), maintains London's main roads, regulates London's licensed taxi service and runs the Tube. The Mayor also sets the budgets for London's emergency services. However, the Mayor of London does not have the same powers as the Mayor of cities like New York and Paris (Hunt, 2005).

The Government Office for London (GOL) represents central government across the capital. Currently, GOL manages over 40 central government programmes, for 10 government departments that include the Home Office, the Department for Education and Skills, the Department of Work and Pensions and the Department of Trade and Industry. The GOL had a budget of £3.3billion (in 2005/6), of which over £2.5billion is allocated to the GLA, Transport for London and the London Development Agency (GOL, 2006b). The GOL liaises with the GLA to ensure that London planning is done within the context of national policy, and leads government responses to the GLA's strategies. There are eight other Government Offices in English regions. London is also unique in England as it has its own Minister.

There are a number of other organisations that represent London, its boroughs or other interest groups (eg. businesses). In terms of climate change there are two main London bodies (although many more local and national groups). The London Climate Change Agency (LCCA) is a group of organisations and businesses working to reduce carbon dioxide emissions in London. Whilst the LCCA's main remit is mitigation, the London Climate Change Partnership (LCCP) focuses on assessing the impact of climate change and identifying adaptation strategies.

2.1.4 Economy

London is a global centre for international business and its economy can be compared in size to many national economies. Over a quarter of the world's largest companies have their European headquarters in London and over 65 percent of the Fortune Global 500 companies are represented in London (ONS, 2003). London's economy is unique in the UK, and in terms of Gross Value Added (GVA)[*] its economic prosperity is higher than the rest of the country and other city-regions in Europe (ONS, 2003). However, GVA in Inner London is three times higher than Outer London and this variation can be even more across NUTS3 regions (see Figure 2-1).

Property, renting and business activities are the major sector in London's economy: both directly in terms of their contribution to GVA (29%), but also in the other industries (*eg.* transport and communications, restaurants and hotels) they help sustain due to their contribution to aggregate spending power. The next most significant sectors in London are wholesale and retail trade (12% GVA); financial intermediation (10.3% GVA); manufacturing (10.2% GVA); transport, storage and communication (9.3%) (ONS, 2005). The remainder is predominantly public sector, education, health and social work, construction and utilities. There are small (<1%) contributions from mining and agricultural industries. This is not reflected across the rest of the UK where financial and business services contribute much less to GVA and manufacturing accounts for more.

One third of London jobs (1.3 million) are in the financial and business services, compared to a national average of 20 percent whilst twenty two per cent of London jobs are in the public sector (ONS, 2006). Workers in London have higher average gross weekly earnings than the rest of the UK but costs of living are generally higher. Unemployment in London was 6.9% in spring 2002, slightly higher than the national average – but contains wide variation in employment rates, including boroughs that consistently have some of the highest unemployment rates in the country (ODPM, 2004c).

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[*] Gross Value Added is the sum of incomes earned from the production of goods and services in the region, when measured by workplace workers who reside outside London also contribute to the figure. Gross Domestic Product (GDP) also includes taxes and subsidies.

Tourism is also a significant contributor to the London economy. London receives over 11 million visitors a year, half of all trips to the UK, with an average visit lasting a week and each visitor injecting over £500 into the economy on average (ONS, 2001b).

2.1.5 Land use

Despite its high population density, London is not entirely built up: whilst the majority is suburban (38%) or urban (20%), over a third is semi-natural, mown grass, tilled land or woodland (CEH, 1991)[*]. In 2002, there was approximately 22,800 hectares of agricultural land, 3,800 hectares classified as Grade I and II arable land (DEFRA, 2002). There are 368 hectares of brownfield land in London (DCLG, 2006).

The urban area consists of over 3 million dwellings (a dwelling can contain multiple households). There are 229,000 commercial or industrial hereditaments (*i.e.* property can be passed on to an heir) with a total floorspace greater than 70 million square metres (ONS, 2003). Almost half of this is retail space, and nearly a third office space (the rest being factories and warehouses). There are also nearly 13,000 listed buildings and 151 ancient monuments (ODPM, 2005).

As in any city in an industrialised country, London contains significant amounts of infrastructure not directly related to the transport or energy systems, but crucial to the functioning of the city. This includes a large number of schools, hospitals, police and fire stations, prisons, post offices and a dense network of telecommunications and other utilities.

2.1.6 Transport

London has transport infrastructure that is in several respects unique in the UK. It is the road, rail and air hub for the UK and has a dense network of private and public transport networks. The rail network consists of 14 major termini providing local, regional, national and international connections. The London Underground is the world's oldest metro service and contains 274 stations and over 400km of track. The London Underground is supplemented by some light rail and tram systems.

In total there are approximately 13,600km road in London that handle approximately 30 billion vehicle kilometres each year. The Highways Agency has responsibility for the 117 mile long motorway, the M25, that encircles most of the urban area of London. Transport for London manages approximately

[*] A more recent landcover map has been generated from more recent satellite data, but the land cover summary data could not be located. However, whilst some changes are likely these are not expected to be enormous.

580km of main road in London that accounts for one third of the traffic, with local authorities managing the minor routes. There are also 54 bridges and tunnels (not including London Underground tunnels) in London.

London also has two international airports within its borders, London City Airport and Heathrow which handles more international passengers than any other airport in the world. There are currently 18 piers serving river transport on the Thames and the number of boat passengers has been increasing steadily. The Port of London is 10km outside the GLA boundary at Tilbury.

As in the rest of Great Britain, car ownership in London is rising. However, even in 2001 more than 50 percent of Inner London households did not have a car because congestion, parking limitations and a frequent and accessible transport network provide disincentives. In Outer London, where these disincentives are not so strong, the figure is comparable to the national average of 28 percent (ONS, 2003, DfT, 2006). The number of motorcycles in use is also increasing.

Table 2-1 and Table 2-2 indicate the relative amount of personal and freight travel by mode in London. In some instances these are not the most recent statistics, which will be gathered as part of this project.

Table 2-1 Distance travelled in miles per person per year (1999-2001) by transport mode (summarised by ONS, 2003 form multiple sources)

Mode	**London**	**Great Britain**[§]
Bus and coach	406	341
Rail & London Underground	996	425
Taxi	79	60
Car/van	3,544	5,566
Motorcycle	45	29
Bicycle	32	39
Walk	237	189
Other	113	166
Total	5,452	6,815

[§] This covers travel for all residents of Great Britain (England, Wales and Scotland), living in private households, within Great Britain for personal reasons, including travel in the course of work, (e.g. a doctor on their rounds or a businessman travelling to a meeting), but not travel by people whose work is to travel (such as bus drivers, postmen and delivery men).

Table 2-2 Freight traffic in London in 2001 by million tonnes lifted (summarised by ONS, 2003 from multiple sources)

Mode	**Destination London**	**National**	**River Thames internal**	**Leaving Port of London**	**From Heathrow**
Road	99	1,581	-	-	-
Rail	5.8	94	-	-	-
Water	-	-	1.9	50.7	-
Air	-	-	-	-	1.16

2.1.7 Greenhouse gas and air pollution emissions

As described in Section 2.1.6, there is significant transport, commercial and industrial activity in London and a large number of households. There are a number of methods available for accounting emissions, which are considered in Appendix F. However, some key emissions results from the London Atmospheric Emissions Inventory 2003 (LAEI: GLA, 2006) are now summarised in Table 2-3. Figure 2-3 provides an indication of the spatial variability of the emissions in London – showing both transport and non-transport emissions. Both greenhouse gas (GHG) and pollutant emissions (although there is overlap between these two categories), yet not all of the GHGs used to define the IPCC (2001a) scenarios, are recorded as the LAEI report focuses on air quality. Table 2-4 compares London's emissions with the whole of the UK (extracted from the National Atmospheric Emissions Inventory 2003: NAEI); from this it can be seen that London contributes significantly towards the UK's total emissions. The LAEI figures have been calculated from the NAEI totals by apportioning emissions based on emissions factors and activity (*eg.* population, energy prices, indicators of economic growth *etc.*) which ensures they are consistent. However, as highlighted in Appendix F, there are other methods that could be employed to calculate the emissions from a city. Although some emission sources may increase (*eg.* air and motor vehicle travel) emissions of all the compounds shown in Table 2-4 are expected to decrease by 2010 (GLA, 2006) and improved air quality is an aim of the London Plan (GLA, 2002c, GLA, 2004).

Three classes of emissions are considered: mobile, point and area sources. Mobile sources include all on-road mobile sources such as motorcycles and cars, and non-road mobile sources such as trains, ships and aircrafts. Point sources include stationary emission sources identified individually due to the quantity or nature of their atmospheric emissions such as regulated industrial processes and large boiler plants. Area sources include facilities whose emissions can not be more accurately specified and whose individual emissions do not qualify them as point sources (individually they emit smaller quantities of pollutants), however; collectively they can release significant quantities of pollutants. This includes domestic consumption.

Table 2-3 Selected emissions by source in London for 2003 (from GLA, 2006 which also reports other emissions)

	NO_x (t/yr)	CO_2 (t/yr)	PM_{10} (t/yr)
Agriculture & Nature	176.04	4,967.85	76.77
Airport	4,137.17	1,137,039.53	118.08
Boilers	209.59	260,004.27	7.55
Coal	0.00	0.13	0.00
Gas	26,213.75	15,566,786.20	187.67
Oil	41.80	46,033.32	0.31
Heavy industry (Part A[**])	5,234.67	8,048,195.82	0.08
Light industry (Part B[*])	336.08	55,874.62	171.33
Rail	3,240.80	193,842.40	82.8
Road transport	27,318.29	7,515,108.23	1,331.70
Sewage	20.08	8,24.91	0.00
Ships	113.63	5,035.70	0.69
Solvents & Building	0.00	0.00	20.13
Total	67,041.91	32,833,730.98	1,979.34

Table 2-4 Total London and UK emissions for 2003 (from GLA, 2006 and Baggott et al., 2005 who also report other emissions)

	SO_2	CH_4	VOC	NO_x	CO_2	PM_{10}
London (kt/yr)	1.5	30.0	62.5	67	32,833	2.0
London (% UK)	0.15	1.17	5.82	3.98	6.01	1.29
UK (kt/yr)	973	2,554	1,073	1,685	546,097	155

[**] Part A, of which there are approximately 2,000 in England and Wales, are major industrial processes that are regulated by the Environment Agency and Part B are smaller scale processes regulated by local authorities.

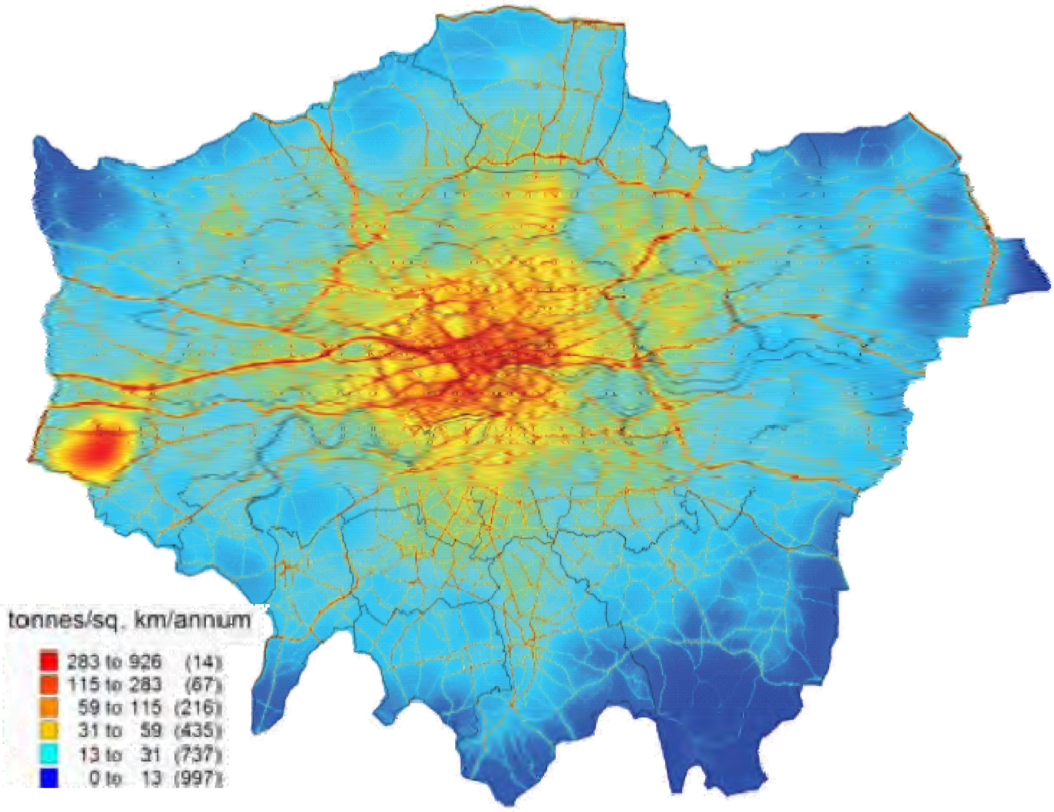

Figure 2-3 Spatial disaggregation of transport and other sources of NO_x emissions in London (© Environment Group, Greater London Authority)

2.2 *Pressures on London*

2.2.1 Climate change

The UK Climate Impacts Programme has provided regional estimates of climate change for South East England (Hulme *et al.*, 2002). The main predicted changes in climate are:

- Summers will be 2.5-5.0ºC warmer and winters will be 1.5ºC to 3.5ºC warmer by the 2080s for the low and high emissions scenarios respectively (Figure 2-4).
- Correspondingly, higher summer temperatures will become more frequent, and very cold winters will be rarer. For example, daily maximum temperatures of 33ºC, which currently occur about one day per summer in the south-east, could occur 10 days per summer by the 2080s for the medium-high emissions scenario.
- In central London, the urban heat island effect currently adds up to a further 5 to 6ºC to summer night temperatures. This may intensify in the future.
- Relative sea level in the Thames Estuary will continue to rise by between 26 and 86cm by the2080s and will rise further in the future. Extreme storm surges may become more frequent.

- Whilst winters may become 10-30% wetter by the 2080s, summers may become drier by 20-50% (Figure 2-5).
- Extreme winter rainfall could occur twice as frequently by the 2080s, although snowfall amounts will decrease by between 50-100%.
- The number of storms each winter crossing the UK could increase by almost 50% by the 2080s, whilst mean winter wind speeds may increase by as much as 10% by the 2080s, though this is very uncertain.
- Summer cloud cover may decrease by as much as 18% by the 2080s, increasing the amount of UV radiation reaching London.
- Summer soil moisture may reduce by 50% or more by the 2080s.

These changes in climate will pose significant challenges for a number of sectors that are discussed in more detail in following sections.

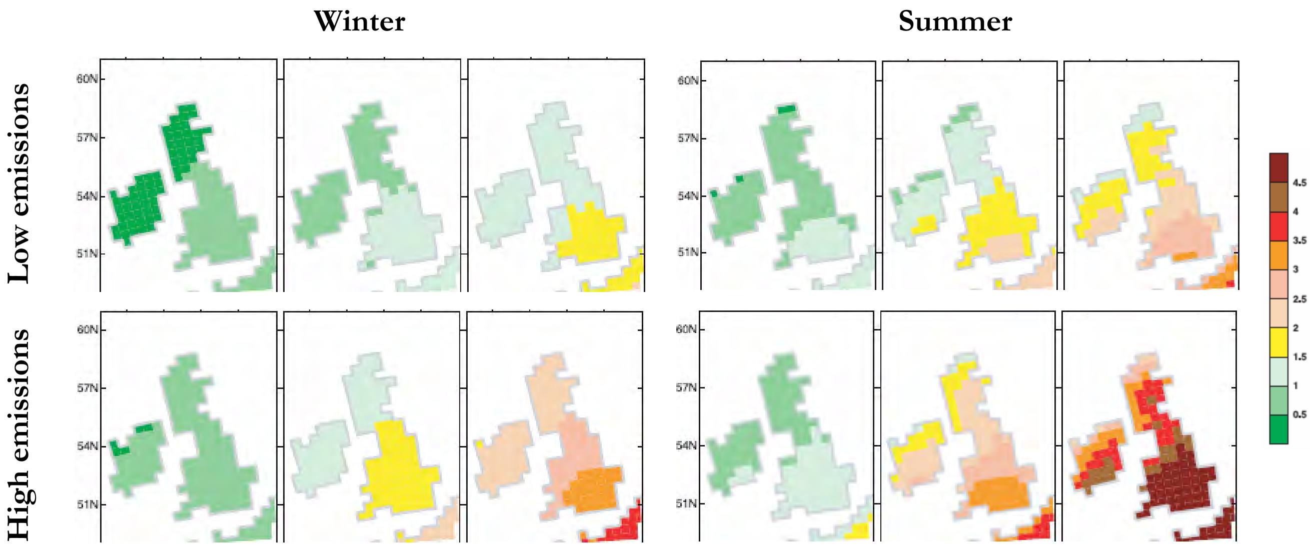

Figure 2-4 Mean temperature change (°C) for low and high emissions scenarios in winter and summer

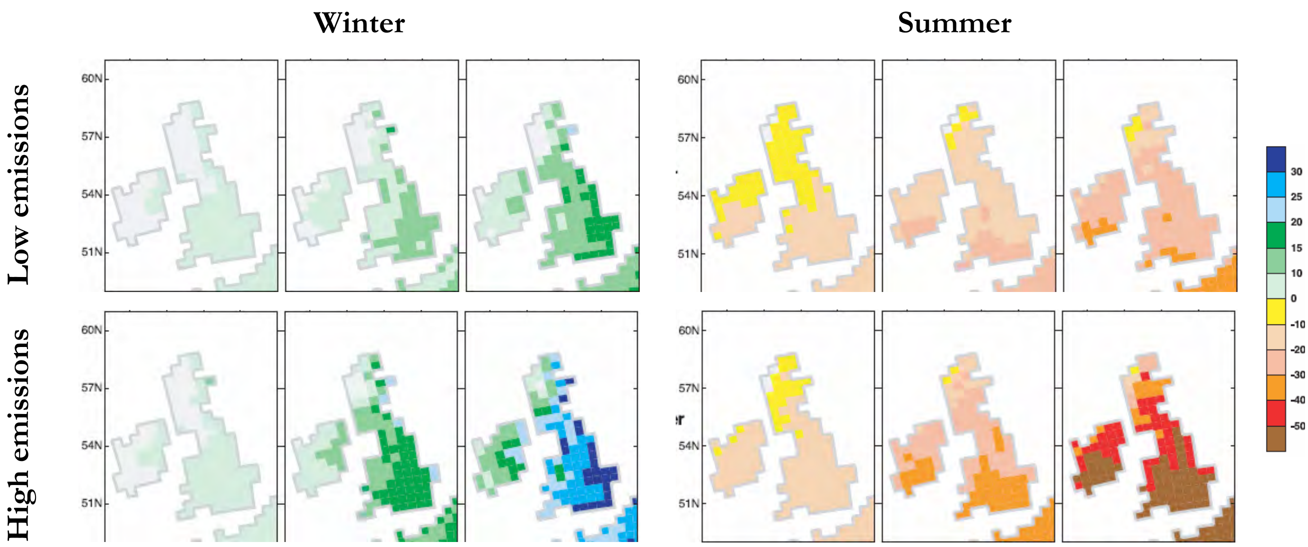

Figure 2-5 Percentage change in precipitation for low and high emissions scenarios in winter and summer

2.2.2 Socio-economic change

The London Plan

The London Plan (GLA, 2004) is the strategic plan setting out an integrated social, economic and environmental framework for the future development of London for the next 15–20 years. The plan integrates the physical and geographic dimensions of the GLA's other strategies that include:

- Climate change,
- Transport,
- Economic development,
- Air quality,
- Waste management,
- Noise,
- Culture, and,
- Energy.

The plan provides the London-wide context within which individual boroughs must set their local planning policies and also sets the policy framework for the GLA's involvement in major planning decisions in London and sets out proposals for their implementation and funding. The salient points are now identified below.

- Accommodate growth within current boundaries without encroaching on open spaces.
- Make London a 'better' city to live in.
- Strengthen and diversify economic growth.
- Increase social inclusion and reduce deprivation.
- Improve accessibility: public transport, cycling, walking (*i.e.* reduce use of cars). However, airport, port and rail infrastructure likely to be increased.
- Make London a more attractive, well-designed green city through improved waste management, re-use of brownfill sites, increased self-sufficiency, improved air quality.

Development zones and planned growth

Despite the dense population in Inner London (see Section 2.1.1), there are currently ten buildings higher than 150m (compared to New York's 184)[††]. However, the London Plan encourages the development of skyscrapers and there are many more planned or proposed high buildings in the near

[††] This information was taken from Wikipedia (2006), http://en.wikipedia.org/wiki/Tall_buildings_in_London; and http://en.wikipedia.org/wiki/List_of_tallest_buildings_in_New_York_City (accessed: October 25, 2006).

future. In the last ten years, the majority of land use change (~85%) has been in areas that have had some form of developed use (DCLG, 2006) and this trend is expected to continue under the London Plan. A number of areas in London are protected from development, this includes historic buildings, parks, Metropolitan Open Land, Special Sites of Scientific Interest (SSSIs) and the Green Belt which aims to check unrestricted urban sprawl of the urban area.

Much of the new development in London is expected to be in the East, along the Thames Gateway corridor (from East London to the Thames Estuary) and in the River Lea valley where the 2012 Olympics will be held. Other major growth areas in the East and South East regions will be Milton Keynes, the South Midlands, and the London, Stanstead, Cambridge and Peterborough corridor. By 2016, development of nearly 500,000 new households and associated infrastructure is planned in these growth areas, with 120,000 of these to be located in the Thames Gateway area (ODPM 2003, ODPM 2004a). The GLA (2005d) argue that London requires over 300,000 new houses by this date (although this figure includes some overlap with the other growth areas). Whilst the actual changes may diverge from the above numbers, the trend is clear. Longer term planning issues are usually evaluated against a number of scenarios which is the subject of Section 3.2.2.

2.2.3 Flood risk

The tidal Thames floodplain includes extensive areas of development along the Thames through London and to the east. Currently there is an area of approximately 345km^2 at risk of flooding which contains:

- 1.2 million people live in the area at risk of flooding;
- nearly 500 Schools and Hospitals;
- 5,540ha of nationally and internationally designated sites of nature conservation importance (representing 16% of all land at risk of flooding);
- 2,450km of transport links (Motorway, A-Road and Rail);
- 516,000 properties in the floodplain of which 476,000 are residential;

The current flood defence system will continue to provide a protection against the 1:1000 year storm surge until the year 2030. The Thames Tidal Defences comprise the Thames Barrier, 185 miles of floodwalls and embankments, 35 major gates and over 400 minor gates. The Thames Barrier is situated in East London between Greenwich and Woolwich is 520m wide and became operational in 1982[♯].

The Thames river defences through central London are designed against the 1 in 1000 year flood event. However this is lower on many of the tributary rivers. Meanwhile, the river Thames is most susceptible to river flooding West of London.

Urbanisation has led to the several rivers in central London now flowing underground. The Environment Agency (2001) estimate that 29 percent of London's river channels are natural, 56 percent are artificially surfaced, and 15 percent are culverted. This has implications for the rate and volume of runoff following extreme precipitation events that overwhelm urban drainage systems, which already account for a significant proportion of flood events (NAO, 2004, ABI, 2004b). As highlighted in Section 2.2.1 these types of events are expected to increase in the future. Changes to groundwater level, river flow or sea level may have implications for sewer flows and associated pumping and treatment costs potentially leading to increased incidents of sewer flooding from separate and combined systems.

2.2.4 Temperature and urban heat island

There are three main features to changing temperatures: changes to annual mean temperature, changes to extreme temperatures and in urban areas the interaction with local climatology that causes the heat island.

Increased temperature can lead to heat stroke, physiological disruption, organ damage, and even death (GLA, 2006). Heat-related deaths could increase to around 2,800 cases per year (compared to an average of 800 currently) and 80,000 days hospital time, although this is likely to be pessimistic in the long-term since no physiological acclimatisation or adaptive changes in lifestyle is assumed, which might be expected if hotter weather became more regular. The 2003 heatwave in Europe resulted in the death of over 2,000 people in England and Wales, and the impact was greatest in London where deaths of people aged over 75 increased by 59%. Raised ozone and PM_{10} concentrations were also observed in London, but attribution of deaths between pollutants and raised temperatures has not been possible (Johnson *et al.*, 2005).

♯ From 1982-2004 the Thames Barrier was been closed 55 times, with 29 of those between 2000 and 2004. However, the barrier closure rule has been changed in order to better manage extreme fluvial flows as well as tidal surges so this does not necessarily provide a clear signal of climate change as this figure does not distinguish between the causes of the closures.

Conversely, milder winters are expected to lead to a fall in up to 20,000 cold-related winter deaths per year and a drop of up to 2m hours hospital time by the 2050s across the UK (DoH, 2003). Likewise, existing and exotic species of flora and fauna have benefited from the increased temperatures, although further temperature increase could lead to increased competition from exotic species (LCCP, 2002, Wilby, 2003).

The urban heat island is caused by the storage of solar energy in the urban fabric during the day and release of this energy into the atmosphere at night. The process of urbanisation and development alters the balance between the energy from the sun used for raising the air temperature (heating process) and that used for evaporation (cooling process). The main mechanisms for this are:

- the cooling effect of vegetated surfaces is replaced by impervious engineered surfaces that have different thermal properties,
- anthropogenic heat sources emitting heat directly into the urban area, and,
- the interaction of buildings and infrastructure with wind and the boundary layer.

The urban heat island intensity, the difference in temperature between inner London and a rural reference point, is usually at a maximum between 11pm-3am (Figure 2-6). The heat island has, on average, become more intense having been measured as ~2°C (Howard, 1820) almost two hundred years ago, 4-6°C forty years ago (Chandler, 1965) and has increased, on average, at a rate of 0.12°C/decade (Wilby, 2003). The urban heat island has been measured as high as 9°C in a recent extreme event (GLA, 2006). The heat island is more intense during the summer than the winter because more energy is received from the sun. Whilst a general rise in temperature over the Southeast of England may be expected to lead to even warmer temperatures in central London, it is less certain whether climate change may result in an even more intense urban heat island. The other key climatological influences on the urban heat island intensity are solar radiation, cloud cover and wind speed and the global climate models predict these with much less certainty. Based on some of the values listed in Section 2.2.1, GLA (2006) estimate that the heat island is likely to be more intense and the number of hours of UHI intensity of 4°C will increase by over 20 percent. However, use of energy intensive devices such as air conditioning, landuse and the configuration of buildings and streets will also play a key role in mitigating (or amplifying) this effect.

The impact on sub-surface infrastructure can be even more pronounced, temperature differentials between the surface and inside London Underground tunnels of 11°C have been recorded (GLA, 2005a).

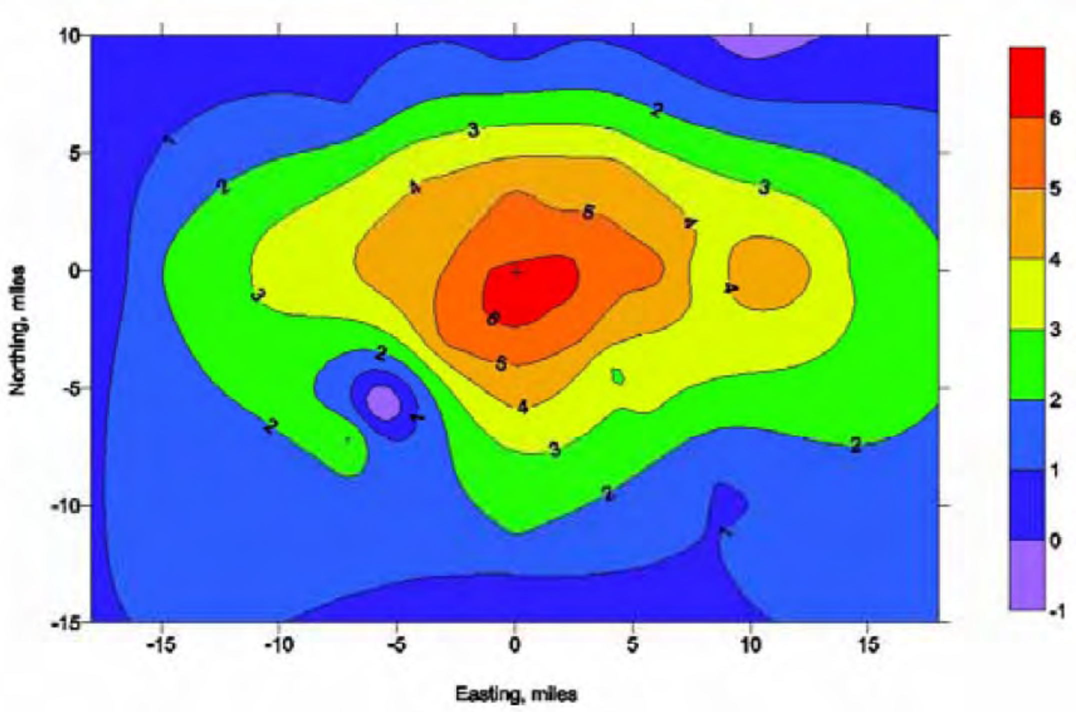

Figure 2-6 Air temperature difference (°C) over London for six urban heat island events between 0200-0300hrs during July 1st-September 30th. The central cross hairs mark the British Museum, whilst the cooler area at the bottom left of London is over Richmond Park. (© Greater London Authority: GLA, 2006)

2.2.5 Air quality

London has contended with air pollution since 13th century industry required burning large quantities of coal. By the 19th century, London was frequently covered by thick fogs. In December 1952, the smog lead to an estimated 3,500-4,000 deaths (ONS, 2003). Legislation was brought in to create smokeless zones which led to improved air quality. However, the increase in motor vehicles (Section 2.1.6) has contributed towards increasing pollution levels, in particular from fine particulates which pose the greatest health risk to Londoners (Fuller and Green, 2006). The GLA (2002) estimates there are 1,600 premature deaths and 1,500 hospital admissions each year from poor air quality in London.

The primary causes of air pollution are nitrogen oxides (NO_x), fine particles (or PM_{10}), sulphur oxides (SO_x), carbon monoxide (CO), benzene, 1,3-butadiene, lead (Pb), ozone (O_3) and polycyclic aromatic hydrocarbons (PAH). Emissions for some of these pollutants are shown in Table 2-3 and Table 2-4. Associations have been reported with daily mortality, health care utilisation, respiratory symptoms, lung function and various other markers such as headaches, dry eyes, nasal congestion, nausea and fatigue (DoH, 2003). Those most at risk are the elderly or young and those with lung and heart conditions. Air pollutants, primarily SO_x and NO_x, also result in acid rain that can degrad ecological and manmade constructions.

Air quality, health and climate change are strongly linked: reduction in greenhouse gas emissions through mitigation strategies will usually result in reductions in other pollutants. In the past it has been poor air quality that has often resulted in reduced pollutants and subsequently greenhouse gases. In general, the effects of air pollutants on health are therefore expected to decline in line with meeting emissions reductions targets. However, climate change is expected to increase the number of warm, still summer days that are associated with ozone pollution events. This could lead to several thousand extra deaths and a similar number of hospital admissions may occur each year (DoH, 2001).

2.2.6 Water resources

Potable water

London is already one of the driest and most populated regions in the UK. It receives approximately 0.02mm of rainfall per person per year which is comparable to Madrid and Istanbul.

Water resources in London are supplied and managed through a network of 32,000km of pipes. The most significant of these is the Thames Water Ring Main which consists of 80km of pipes which transports approximately a third of London's potable water. Much of the pipe network is ageing: 50% is over 100 years old, and 30% over 150 years old. This is further aggravated by London clay through which many of these pipes run as it increases corrosion of the water mains. Pipes can be further stressed by expansion and consolidation of the clay from surface loading or seasonal changes (Thames Water, 2004) and this can lead to increased mains leakage (Doornkamp, 1993).

London's reservoirs, some almost 200 years old, are capable of storing 300 million m^3 water (Hunt, 2005), and Londoners use approximately 2.8million m^3/day and 0.9million m^3/day is lost to leakage. Compared to the rest of the UK, London is more vulnerable to changes in the surface water regime as this supplies 80% of its water resources (Thames Water, 2004), compared to a UK average of 30%. Moreover, London uses 60% of all directly available water resources. Reduced precipitation will lower the available volume of surface water further stressing London's water supply – population growth will place further strain on water resources, and a warmer climate may have a positive feedback increasing household demand. Furthermore, higher summer temperatures and lower rainfall may reduce soil moisture and groundwater replenishment which may not be fully compensated by increases in winter rainfall. Currently, two large infrastructure schemes: a reservoir at Abingdon capable of holding 150million m^3 water, and a desalinisation plant capable of supplying 0.15 million m^3/day are being evaluated as potential adaptation responses.

Sewage and water quality

Water quality in the river Thames and surrounding canals and tributaries has improved over the last couple of decades and 90 percent of the total watercourse length in London are regularly rated fair or above. From 2002-2006 there were 51 pollution incidents in the Thames basin that had a major impact (Environment Agency, 2002-6), although its is still the world's cleanest metropolitan river (Hunt, 2005).

Water quality in the Thames and its estuaries will be most aggravated by climate change during the summer months due to urban run-off from more intense summer storms. Furthermore river flows are likely to be lower in summer, which will raise water temperatures regardless of any ambient temperature increase. The Environment Agency has powers to request improved effluent quality from sewage treatment plants during the summer and to suspend abstraction in order to increase freshwater flows into the estuary. Water quality can also be improved through deployment of oxygenation vessels or use of hydrogen peroxide. Other options may include the introduction of changes to abstraction licensing to allow for increased flexibility in water resource planning.

Evidently in summer months, climate change may increase the tension between providing suitable freshwater supply to London's population and ensuring adequate water quality. This may be further aggravated by more intense summer storms resulting in increased combined sewer overflow (CSO) spills further contaminating the river water. However, there are proposals for a new sewer collector. Borehole water quality tends to be better than surface water and requires less treatment due to the natural filtration properties of the soil, although urbanisation threatens to reduce the quality of water entering underground aquifers.

2.2.7 Wind

The mean annual wind speed in London is 10.5 knots (5-6m/s) (DTI, 1999). However, gusts of 82 knots (42m/s), estimated to be the 1 in 200 year wind storm (the 1 in 50 year gust speed is 36 knots), have been recorded in central London – although for this event the mean wind speed over a ten minute period did not exceed 44 knots (Johnson 1996, Met Office 2006).

The influence of climate change on wind is highly uncertain. However, an increase of winter daily average wind speeds by as much as 10% is suggested by climate models, although this assumes no exchange to extremes (Hulme *et al.* 2002, GLA 2002). On average 200,000 buildings are damaged by wind each year (ABI, 2003) and any change to wind speed or extremes could have a significant impact on buildings which are currently designed according to BS6399 (BS, 1995) to deal with a mean speed of approximately 21 knots in London (although new Eurocodes are likely to increase the design standard).

Wind storms can also result in significant disruption to civil infrastructure (Jonhson, 1996). Furthermore, any increase in the frequency of severe winter storms could lead to an increase in personal injury or death from flying debris and falling trees.

Figure 2-7 shows the wind rose for London with East being the prevailing wind direction. However, it is usually the winds from the North and West that result in storm surges that pose the greatest threat to tidal flooding. Whilst increased wind speeds will result in larger storm surges, changes to extremes and wind direction may also alter their direction.

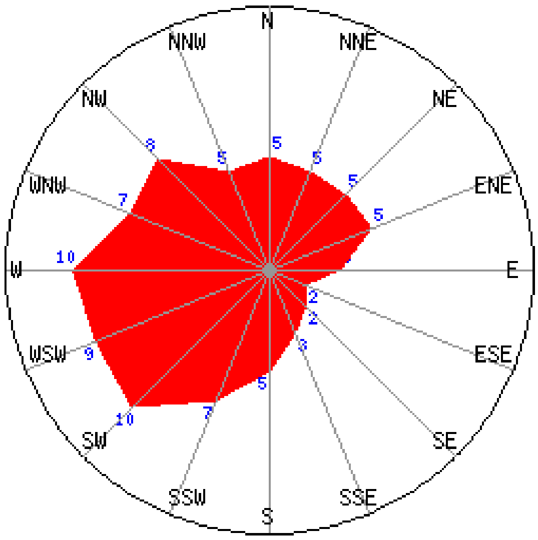

Figure 2-7 Wind rose, showing distribution of direction as a percentage, at Heathrow airport, 2005-2006 (© www.windfinder.com)

2.2.8 Subsidence and heave

Building foundations and underground infrastructure are threatened by subsidence and heave. Mechanisms for this are influenced by loading based consolidation and shrink/swell movement of the London Clay layer and groundwater movement. Older buildings are often more vulnerable as, if they are of non-standard design, they are less likely to be readily adaptable. Furthermore, their initial design is less likely to have encompassed subsidence factors and there may be regulatory obstacles to any major alterations.

Higher temperatures and longer summers will lead to drier soils causing shrinkage of the clay layer beneath London. This could lead to increased subsidence of buildings and infrastructure. In 2003, the insurance industry reported claims of £400m and expect the annual average to be £600m by 2050 (ABI, 2004c). Underground infrastructure, including utility lines and the London Underground could also be damaged, resulting in business and service disruption.

For several centuries, commercial and industrial use led to a significant lowering of the groundwater level in central London (Figure 2-8). Thereafter, reduced abstractions lead to a reversal of this trend, such that water levels are rising rapidly, threatening tunnels and building foundations in central London (Environment Agency, 2001).

The rate of rise in groundwater levels in London could be changed by increased winter rainfall although this is uncertain as the average annual rainfall will decrease. However, a possible impact of rising groundwater is the build-up of pressure beneath the clay layer which sits above the chalk aquifer leading to a slow increase in the saturation of the clay. This could affect the stability of foundations and sub-surface infrastructure, most notably tall buildings and tunnels which are drilled through the clay (ABI, 2002). Overall, this could lead to higher moisture differentials: shrinkage at the surface and saturation at depth.

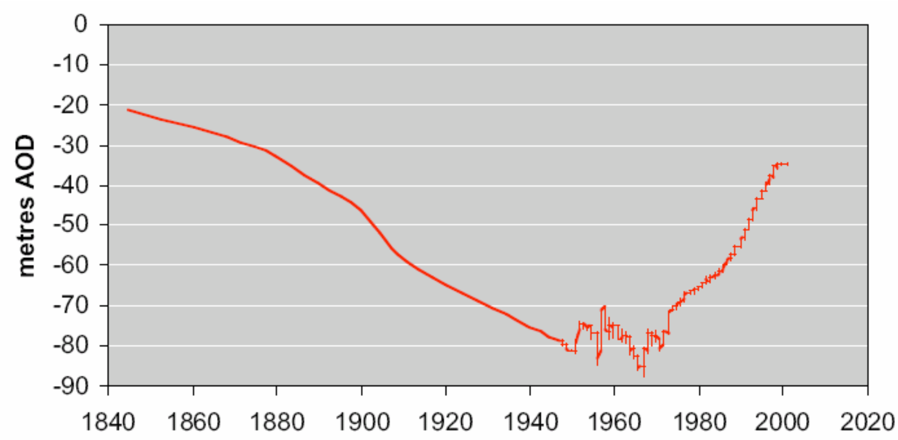

Figure 2-8 Groundwater levels in Central London (© GLA, 2002a)

2.2.9 Disease and other health effects

A study by the Department of Health (DoH, 2001) estimated the impact of a Medium-High emissions scenario on disease and other health effects. This section summarises the findings of this report.

<u>UV exposure</u>

Levels of UV radiation reaching the earth's surface may increase due to sunnier summers, a decline in cloud cover and upper atmosphere ozone depletion would reduce the capacity of the atmosphere to absorb UV. Whilst the impact will depend on behavioural changes, the DoH assessment predicted an extra 5,000 cases of skin cancer and 2,000 of cataract per year by 2050 in the UK.

Vector-borne diseases

Various diseases transmitted by mosquitoes or ticks are climate-sensitive and can increase or be introduced due to climate change. A potential candidate is the re-establishment of malaria in the UK, although this is likely to be localised, with more cases being imported among travellers returning to the UK. The emergence of tick-borne encephalitis is unlikely; the impact of climate change on the incidence of Lyme disease is difficult to predict. Monitoring will also need to look for the emergence of other vector-borne diseases, such as West Nile Fever which is threatening Southern USA.

Water-borne disease

Climate change might increase levels of cryptosporidium and campylobacter in water. Secure sanitation systems should safeguard supplies of drinking water, but possible contamination of stormwater outflows could carry disease into basements and nearby rivers, affecting the health of residents and river users.

Food poisoning

Higher temperatures in summer could cause an estimated 10,000 extra cases of salmonella infection per year in the UK.

Noise

Noise pollution is not a direct climate impact, but is closely linked to transportation and so is highlighted briefly here. The London Household Survey (GLA, 2003) highlighted road traffic noise as being a serious problem for 15 percent of Londoners. This was followed by aircraft, noisy neighbours and building works. The London Road Traffic Noise Map (DEFRA, 2004) modelled noise exposure and identified 0.2 percent of the population of London being exposed to a (weighted) average over the day, evening and night, L_{den}, noise of >75dB (vacuum cleaner at 1m) and 28 percent exposed to >65dB (busy restaurant). The health effects of noise are difficult to quantify, although may include stress, sleep loss and hearing loss. However, noise exposure of L_{den}>65dB is likely to annoy (defined as a feeling of displeasure) 35 percent of people exposed whilst L_{den}>75dB will leave over 60 percent of people annoyed and 37ercent highly annoyed (EC, 2002). Evidently increases to traffic volumes, aircraft flights and construction may lead to increased impacts of noise pollution. Conversely, a shift to electric vehicles and low emissions aircraft could have a beneficial side effect on noise pollution.

2.2.10 Broader interactions

Waste

As in any urban area, London generates a large volume of waste. As highlighted in Section 1.3.2, the relationship between climate change and waste management is not as direct as flooding or water resources. London generated 17.2million tonnes of waste in 2001, approximately 26 percent was municipal (*i.e.* from households, hospitals, educational establishments and some commercial premises) with the rest shared almost equally between the commercial and industrial sectors and the construction and demolition sectors (ONS, 2003). Of this, 7.5m tonnes were recycled (mainly consisting of construction waste). From the municipal waste, some 65 percent was transferred to sites outside of London for land filling, whilst 9 percent was incinerated with energy recovery.

Waste management has implications in terms of emissions generated (*eg.* from landfills, processing and transportation), energy generation and more generally in the context of sustainability and resource use (DEFRA, 2005a). Furthermore, increased temperatures will result in higher rates of refuse decay implying need for more frequent waste collection. Evidently sustainable waste management can provide significant opportunities for climate change managers.

Biodiversity and ecology

Over a third of London's area is green space and open water and is rich in biodiversity in comparison to both UK and other world cities (Hunt, 2005). London contains over 1,500 plant species and 300 bird species including some rare species found in the nature conservation areas and parks, whilst the Thames contains over 100 species of fish (LBP, 2006).

Changes to precipitation and temperature regimes are expected to amplify existing stresses such as habitat degradation, the introduction of aggressive species, water and air pollution, poor management and development of sensitive areas, whilst sea level rise may place further 'squeeze' on coastal habitats (see Wilby and Perry (2006) for a thorough review).

Temperature increases could assist the spread of pathogens and pests affecting flora and fauna. Increased summer drought risk could have detrimental effects on wetlands and woodland (GLA, 2002a). Changes to phenology, such as the emergence of leaves and flowers in spring or frost frequencies, have already been observed in the South-east of England (Wilby and Perry, 2006).

Resource supply and urban 'footprint'

Like all major settlements London is not an isolated city and interacts strongly with the rest of the UK, Europe and the rest of the world. As can be inferred from other sections in this Chapter, this interaction occurs through a complex network of flows of energy, transport, materials, food, waste and water. For example, over 80% of food consumed in London was imported from outside the UK (DEFRA, 2001).

The ecological footprint of an individual or population relates consumption of natural resources to ecological sustainability by aggregating impacts to a common metric of land and sea global hectares (gha). A recent exercise in calculating the urban 'footprint' of London estimated it to be 49m gha, or 6.63gha per capita which compares to a global share of 2.18 per person were global resources distributed evenly (BFF, 2002). This figure neither includes the additional 0.9gha per capita 'natural' land required to maintain biodiversity nor the 'footprint' in other regions (for example, the energy used in manufacturing foreign products consumed in London), although the figure may include some double counting due to the difficulties of tracking resources from their source to final product.

Climate and 'business as usual' socio-economic change are likely to place increased stresses on these resources, both locally and within the global context. First, the global share of 2.18gha is predicted to reduce to as little as 1.44gha by 2050 (BFF, 2000), caused mainly by global population growth. Moreover, changes to climate and demand for resources of those outside London may alter these flows (*eg.* due to changes in consumer habits due to changed climate or socio-economic conditions), or limit their potential (*eg.* due to changes in maximum agricultural productivity, or resource shortages in other regions).

2.3 *Stakeholders*

A review of stakeholder perspectives and policy questions was undertaken through a series of meetings and the literature review in Section 2.1 and 2.2. This interaction with stakeholders will be ongoing throughout the project in order to:

- Define policy questions, in particular those that are not being addressed by other initiatives.
- Envision urban futures and strategies for mitigation and adaptation.
- Understand decision-making processes.
- Access datasets and collaborate with other climate-related initiatives and research.

A brief introduction to key stakeholder organisations and relevant literature follows. The stakeholders contacted, or whose documentation have been the subject of literature review are listed in Table 2-5. The key policy issues identified as part of this review and engagement process are listed in Section 2.4.

Table 2-5 Stakeholders contacted for the Tyndall Centre Cities Programme[§§]

Organisation	Key responsibilities and interests	Contact
Association of British Insurers (ABI)	Representatives for the British insurance industry. Their main interest is in risks insured by the companies they represent. These are predominantly: flooding, windstorm, subsidence and health.	Literature review; Meeting 2005.
Environment Agency (EA)	Quasi-autonomous non-government organisation with a wide range of responsibilities. A key interest is flood risk management, and they lead the TE2100 team planning London's tidal flood defence for the 21st century. The EA are also have a duty to secure the proper use of water resources, water quality, and environmental pollution.	Literature review; Meeting with TE2100 representative June 2006.
Government Office of London (GOL)	Represents central government across London and ensures that London planning is done within the context of national policy.	Meeting June 2006.
Greater London Authority (GLA)	Responsible for social, economic and environmental planning for London (see Section 2.2.2).	Literature review; Meetings with GLA climate group (January 2006, July 2006) and economics group (November 2006).
London Climate Change Agency (LCCA)	Aim to reduce London's GHG emissions through deploying more efficient technologies and changing London's energy generation portfolio.	Literature review; Meeting November 2006.
London Climate Change Partnership (LCCP)	Aim to help ensure that London is prepared for climate change. A partnership of organisations interested in the impacts, and possible adaptation strategies in London. They have a particular interest in transport systems, growth areas and the financial service industry.	Meeting proposed
Thames Water	Commercial company answerable to customers and	Meeting May 2006

[§§] Interaction with stakeholders is ongoing and this list is not a definitive list of all organisations with an interest in climate change impacts in London but should enable our project to engage with a broad range of policy makers.

(TW)	shareholders. Their main responsibility is water resources, but they are also concerned with matters relating to sewage, urban flooding and water quality. They are the main water supplier to London, the other companies being: Three Valleys Water, Sutton and East Surrey Water Company and Essex and Suffolk Water Company.	
Transport for London (TfL)	Responsible for managing the majority of London's transport system (including the London Underground).	Telephone and email contact.
London Sustainability Exchange (LSx)	Aim to accelerate the transition to a sustainable London by connecting and motivating people.	

2.4 *Key policy areas*

Key policy questions raised during the preliminary stakeholder reviews have been identified. The full list of specific questions, and the extent to which they can be addressed in this programme is listed in Appendix L. Those that can not be addressed within the current research programme will help inform further research needs. Key policy areas for London are:

- The effectiveness, and economic impacts, of taxation at reducing emissions.
- The role of land use planning in reducing emissions and climate vulnerability.
- The effectiveness of regulation and technology at reducing transport emissions from tourists, commuters and freight.
- How London might achieve a 60% reduction in non-transport emissions.
- The impacts of climate and socio-economic change on flood risk, water resources and heat stress and how to manage these risks.
- Trans-sectoral issues requiring an integrated assessment in order to identify the win-win measures that will help reduce climate risks whilst also reducing emissions.
- Uncertainties associated with future climate impacts, emissions and adaptation and mitigation responses.
- The effectiveness of the timing of implementing the response measures, and the effectiveness of different portfolios of responses.

Chapter 3 Blueprint for an integrated urban climate impacts assessment framework

This Chapter introduces our blueprint for an Urban Integrated Assessment Framework (UIAF) for climate impacts and emissions accounting. This Chapter aims to give an overview of the UIAF and the key interactions between the different models used. More detail is provided on each model and their respective interactions in the Appendices. Preliminary requirements for the user interface scenario building and other components of the UIAF are outlined. Details of the interactions are provided in Appendix J.

3.1 *Overview of the UIAF*

On the scale of large cities it is meaningful to think about climate impacts, adaptation and mitigation in the same quantified assessment framework. This is a scale at which strategies for mitigation and adaptation can be usefully designed and assessed. Yet urban climate mitigation and adaptation policy and behaviour can hardly be divorced from its global context. Our framework for integrated assessment, shown in Figure 3-1, therefore is driven by a coupled global climate and economics model. This provides the boundary conditions for the city scale analysis, in this case study London. These boundary conditions drive scenarios of regional economy and land use change, ensuring that whilst they are influenced by local policy, these scenarios are also globally consistent. It is at the level of land use modelling that the analysis becomes spatially explicit. Scenarios of land use and city-scale climate and socio-economic change inform the emissions accounting and climate impacts modules. The final component of the framework is the integrated assessment tool that provides the interface between the modelling components, the results and the end-user. These components are discussed in more detail in the following sections.

This is a generic framework for climate impacts analysis on urban systems. The models presented in subsequent sections are also generic in that they can, and in most cases have, been demonstrated on other case study sites. However, the framework for urban climate impacts analysis is not constrained by particular models, but in order to implement it a number of key modelling principles must be implemented:

- The UIAF is set within the context of global climate and socio-economic change.
- Global or regional predictions of climate and socio-economic change are downscaled to the urban area enabling the impact of global mitigation to be explored at the city-scale.
- Within the bounds of a given global scenario, national or city-wide economic and landuse policy can be tested: this does not necessarily have to coincide with the global trajectory.

- Emissions accounting and climate impacts assessment are informed by scenarios of economic and landuse change, whilst being consistent with scenarios of climate change.
- Adaptation and mitigation scenario developed within the UIAF must be consistent both internally and within the broader context of global change scenarios (*eg.* the limits to the effectiveness of technology to mitigate transport emissions in London can not exceed the assumed level of technological advancement in the global scenario).
- The boundaries of analysis for impacts assessment and emission accounting are not necessarily identical (although always extend at least as far as the urban boundary) but they may often be extended to be more relevant in the context of decision-making (*eg.* addressing an entire fluvial catchment when considering water resource issues).
- The resolution of the output may vary according to the accounting or impact being considered; this may require additional downscaling.
- The UIAF considers a finite number of scenarios of cliamte change, but allows a much richer range of city-scale scenarios to be explored.
- To maximise the number of policy questions that can be tested, the models must be implemented such that results are rapidly realised. This can be achieved using a number of approaches including: use of rapid and/or low-complexity models, pre-running a wide range of scenarios and storing the outputs in a database and the construction of model emulators.

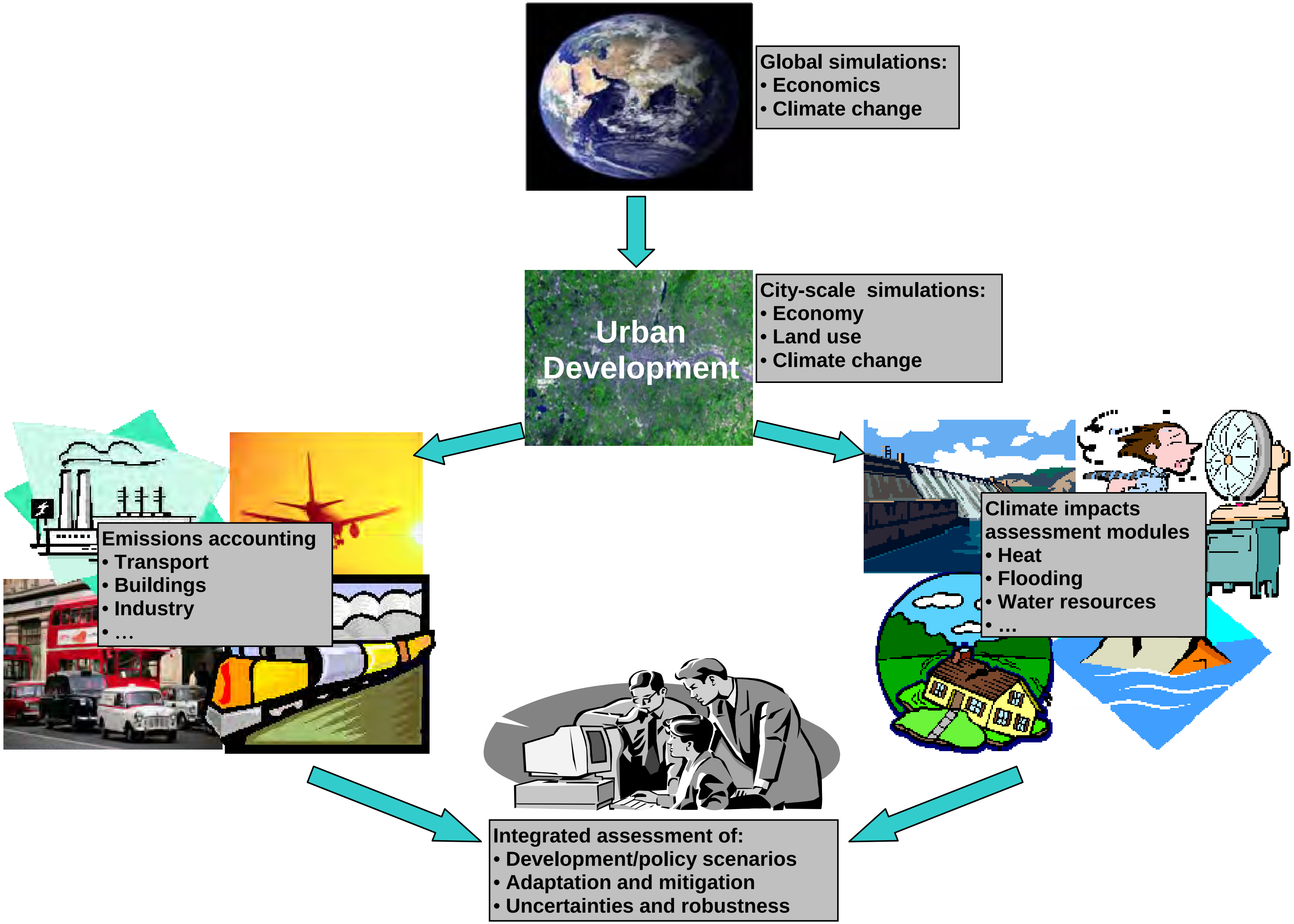

Figure 3-1 Overview of the Urban Integrated Assessment Framework

3.2 *Construction of an integrated assessment model*

This section outlines the key features of the integrated assessment model, provides a brief introduction to the models employed in this case study and the main interactions between the different models. The models, their inputs, outputs and more technical information is provided in Appendices C-I.

3.2.1 Global climate and socio-economic scenarios[***]

Scenarios represent alternative storylines of the future rather than predictions or forecasts. Analysis of a set of scenarios can assist in the understanding of the behaviour and long term changes to complex systems to support policy making (Davis, 1999). Future levels of global GHG emissions are the products of a complex dynamic system that is driven by changes in population growth, socio-economic development, technological change, values and policy. Whilst changes to GHG emissions may have significant impacts on global climate change, accurate prediction of emissions is impossible. Scenarios provide an internally consistent and reproducible set of assumptions about the key relationships and driving forces of change in order to integrate qualitative narratives about future global change and quantitative estimates of future emissions scenarios.

Significant development of coupled global climate and socio-economic scenarios has already been achieved. We do not propose to develop new global scenarios in this program but to use established and internationally credible scenarios. Three scenario programmes are considered and briefly summarised below:

1) The (SRES) scenarios used in the IPCC third assessment report (Nakicenovic *et al.*, 2000).
2) The (CPI) Common POLES-IMAGE scenarios that represent an update to several SRES scenarios (Criqui *et al.*, 2003).
3) The UK Foresight Scenarios (DTI, 2002).

In the context of the urban management, these scenarios, and their associated parameters, are outside the control of city planners – but do play an important role in influencing urban policy.

<u>SRES scenarios</u>

The forty SRES scenarios are grouped into four 'families' of futures (Figure 3-2) based on the main trends in the broad social, economic, technological, environmental and policy parameter space. Each

[***] A full review of global, national and London socio-economic scenarios is underway. This review will gather available data on economic activity and population at each of the scales, as well as comment on downscaling methodologies, for scaling between the three different resolutions of scenarios. This review will provide the evidence base for parameterising the MDM-UK model for the baseline and other global coupled climate and socio-economic scenarios.

family consists of a number of scenarios; the main features are described below (Nakicenovic *et al.*, 2000):

- **A1 scenario family**. Very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies leading to increased capacity building, cultural and social interactions and a substantial reduction in regional differences in per capita income.
- **A2 scenario family**. High population growth with fragmented and slow per capita economic growth and technological change.
- **B1 scenario family**. Low population growth, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
- **B2 scenario family**. Moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. The emphasis is on local solutions to economic, social, and environmental sustainability.

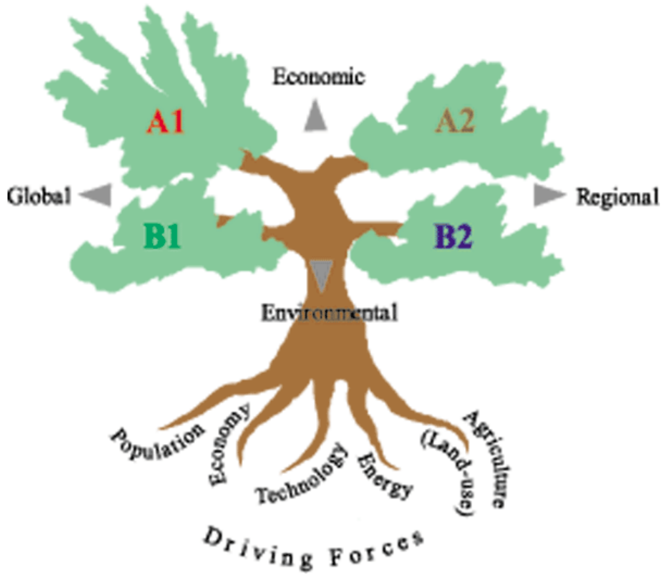

Figure 3-2 A simplified schematic of the SRES Scenarios plotted on a two-dimensional axis showing the tensions between regional vs. global emphasis and environmental vs. economic emphasis (Nakicenovic et al., 2000)

CPI scenarios

The CPI scenarios provide alternative global scenarios to the SRES scenarios; the most significant difference is that the CPI scenarios assume lower population growth over the 21st century (Criqui *et al.*, 2003). The baseline scenario describes a world in which globalisation and technology development continue to be an important factor behind economic growth, although not as strongly as for instance assumed in the SRES A1 scenarios. Economic growth is therefore assumed to reach a moderate level in almost all regions. Several additional greenhouse gas mitigation scenarios were considered relative to this baseline.

UK Foresight scenarios

The UK Foresight program has developed a set of storylines that consider four possible socio-economic futures of the UK in relation to two drivers of change: social values and systems of governance (Figure 3-3). Although these are UK-centric scenarios, they are set within a global context. Social values range from individualistic values to more community orientated values and the resultant pattern of economic activity. Governance addresses the structure of government and the decision making process, ranging from national autonomy to interdependence where power increasingly moves to other institutions e.g. up to the EU or down to regional government. The main drivers are:

- economic and sectoral trends (including energy),
- employment and social trends,
- regional development and international context,
- health, welfare and education,
- the environment.

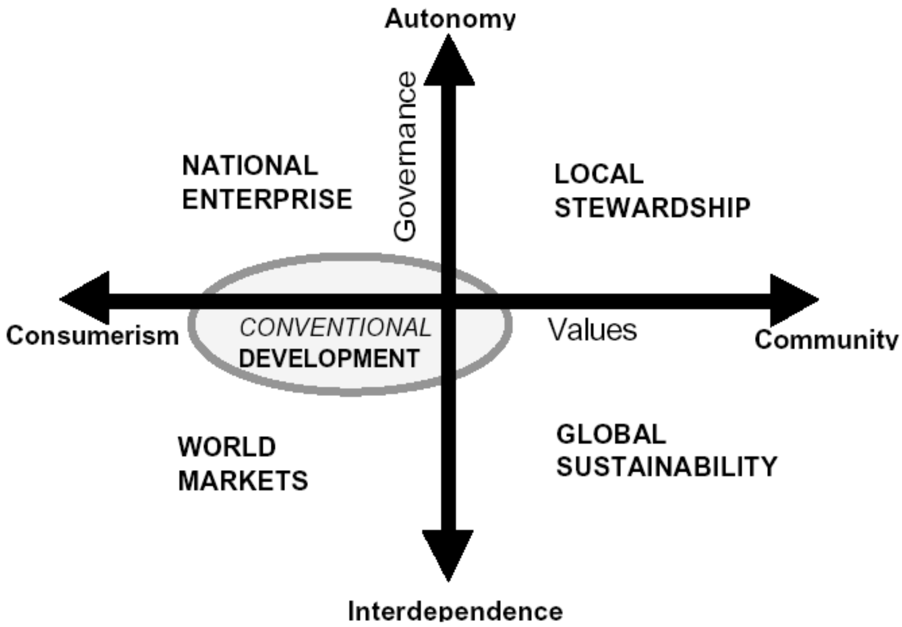

Figure 3-3 UK Foresight scenarios plotted against governance and values

These socio-economic scenarios have been coupled with four of the SRES GHG emissions scenarios for the UK Climate Impacts Programme (Hulme *et al.*, 2002, UKCIP, 2001).

3.2.2 Downscaling global change to an urban scale

Socio-economic attributes

Evidently, the resolution of the socio-economic parameters described in Section 3.2.1 is too coarse to describe changes in individual cities. As already stated, a key component of the UIAF is the downscaling of global or regional socio-economic variables to a city scale. A review of available models has identified the Multisectoral Dynamic Model of the UK (MDM-UK) (Cambridge Econometrics, 2003 and Figure 3-4) as the most suitable for the current application. This model also has the same structure (and was developed by the same organisation) as the REEIO (Regional Economy-Environment Input-Output) model which has been used in previous studies by GLA economics. However, the MDM-UK model is currently a medium-term forecasting model (up to 2020) and will therefore be extended until 2100 as part of this study. Using the MDM-UK model will limit the number of economic scenarios to be limited to a pre-selected finite number. However extension of the MDM-UK model to 2100 enables the impact of structural changes to the economy to be explored (*c.f.* Köhler, 2003).

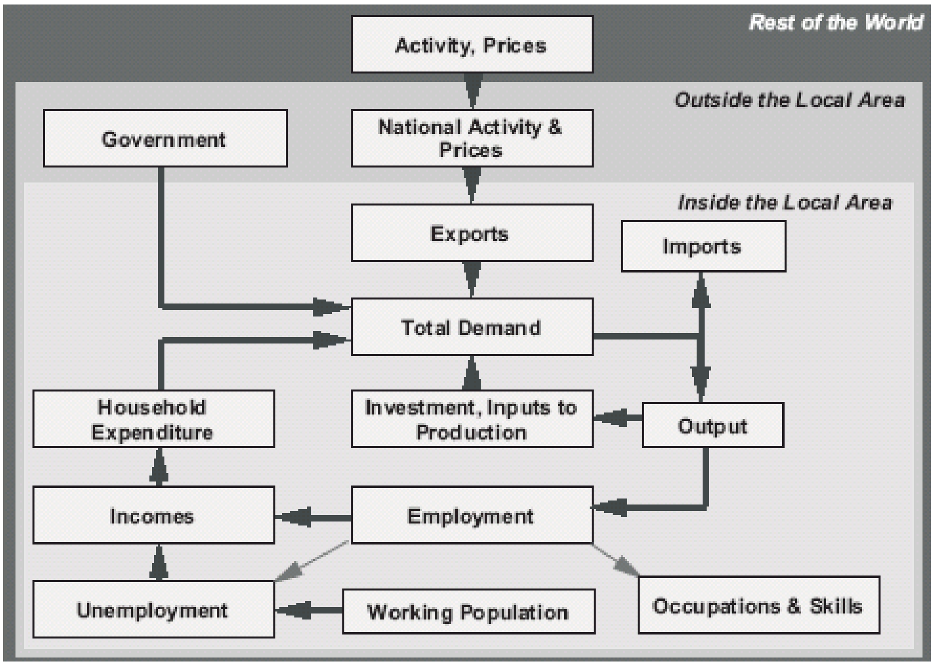

Figure 3-4 Structure of the MDM-UK and REEIO models (Cambridge Econometrics, 2003)

Global socio-economic scenarios contain parameters such as population growth, GDP and global emissions. Global socio-economic scenarios are only reported at the European and global level, whilst MDM-UK is driven by UK estimates. Therefore, a relationship between the UK and European and/or global parameters, such as population growth, will be established. This relationship will be based on the results of a literature review of available UK scenarios and analysis of past trends. In order to account for the downscaling uncertainty this may incorporate into the modelling process, several plausible relationships will be established.

The effect of selected national or international policies on the city-scale economy can be tested and at the city scale economic policy instruments such as a carbon tax (*eg.* congestion charging) may be tested. The impacts of climate change on the national or global economy and its knock-on effects at a city scale can potentially be tested. A limited number of 'worst case' impact scenarios may be considered such as the implications of a severe weather related disaster striking London[†††]. City-scale economic instruments can be used to explore the impact on a cities economy of 'going alone' on imposing stricter (or not) city-scale mitigation policies than external areas.

Climate scenarios

To estimate the impact of climate change on cities it is necessary to downscale global estimates of climate change to the geographical location of the city to provide local estimates of temperature, precipitation and sea level rise. The UKCIP02 study (Hulme *et al.*, 2002) provides the most recent analysis of climate change in the UK using the Hadley Centre's HadRM3 Regional Climate Model. Although less coarse than a global climate model, the resolution is only 50x50km (*i.e.* an individual grid square is larger than the area of Greater London). Whilst estimates of sea level rise from Hulme *et al.* (2002) may be used directly in a flood risk analysis, other climate impacts require further downscaling, both spatially and temporally, from Hulme *et al.* (2003) or other modelling exercises (*eg.* IPCC, 2001a, Christensen *et al.*, 2002) to be useful in a climate impacts analysis.

The most important climate variables for use in the UIAF are precipitation and temperature. Other variables that may be useful for further impacts module development include wind and cloud cover. There are two main techniques for downscaling climate variables:

1) Pattern scaling, and,
2) (Stochastic) weather generators.

Pattern scaling interpolates between measured and modelled variables. It assumes the climate model response pattern adequately represent the behaviour of the climate and that these response patterns are representative across a wide range of conditions. Weather generators produce synthetic time series of weather data by fitting the interannual variability of the observed weather to model variables. The Earwig model, described briefly in Appendix H is an example of a weather generator. Both types of model can be further sub-divided according to different techniques for implementing them. In the context of the UIAF, downscaled timeseries of precipitation, from the Earwig weather generator, will

[†††] There is evidence of cliamte related impacts such as droughts having severe national scale economic impacts (http://news.bbc.co.uk/1/hi/business/6212608.stm), the impacts of floods and other disasters are also well reported (*c.f.* Mileti, 1999)

be used in the water resource and flood impacts module, whilst in the high level heat impacts module pattern scaling will be used to estimate temperature changes.

3.2.3 Modelling urban land use

A number of modelling approaches, ranging from system dynamics and landuse allocation models through to agent-based models of individual (or group) behaviour have been used to simulate regional and urban landuse change (Gilbert and Troitzsch, 1999, Waddell, 2002, Emmi, 2003, Benenson and Torrens, 2004, Fontaine and Rounsevell, 2005). These methods have varying data requirements and associated computational expense.

The UIAF will incorporate a landuse allocation model that accepts exogenous geographical and demographic data and then distributes this demographic information to small areas of the system. In this case, our exogenous demographic data is taken from the output of the economic modelling activity described in Section 3.2.3, and reported by the landuse model for each Ward (ONS, 2004b, Section 2.1.2) geographical unit.

The links between population and employment are simulated as spatial interaction models based on gravity concepts and thus require networks and travel times/costs/distances which are obtained from spatial datasets (*eg.* Ordnance Survey's MultiMap) and travel survey information (*eg.* TfL, 2001, DfT, 2006, Annual Business Inquiry, 2007). These outputs, in terms of population and employment, are then converted to land uses. The landuse allocation model will be extended into the Thames Estuary to incorporate key London growth areas of the 21st century. The model also captures the interactions between London and the surrounding government regions (*i.e.* Southeast and East of England) that contain a large number of commuters. The results of the simulation are reported at the ward level and subsequently used in the climate impacts analysis. However, for certain impacts it may be necessary to downscale to a finer resolution. The landuse model also informs future non-transport emissions, and can be used to test a pre-defined finite number of transport scenarios as described in the following section.

Land use policy can be tested through the use of uniform or spatially variable parameters that increase the likelihood of certain types of development (*eg.* high density living), or reduce (or halt completely) the potential for developing certain types of land (*eg.* protected parks, floodplains). These types of policies can usually be controlled to some degree by urban planners. An example might include testing the policy to develop preferentially on brownfield land as recommended in the London Plan.

3.2.4 Emissions accounting

Transport emissions

The transport emissions accounting methodology will develop methods for the allocation of:

- Personal transport, and,
- Business travel and freight.

And will include the following modes of transport:

- Road (including bus, coach, taxi, car, van, motorcycle and bicycle),
- Rail (including national, local and London underground services),
- Water, and,
- Air.

A key methodological issue in transport emissions accounting is that of attribution. For example, how should emissions associated with a commuter be apportioned between the start and end of their journey? The same issue applies to emissions attribution of aviation, shipping, tourism and freight journeys. For example, emissions could be attributed:

- To the region that benefits from the economic activity of the journey,
- Shared between the starting or end point of the journey, or,
- Apportioned according to where the energy was generated for the journey (for example, a rail commuter on an electric line may use energy from several regions along the route of their commute).

A full review of these and other approaches is underway. In particular, it is necessary to ensure that journeys that pass through multiple regions are not double counted. The allocation of emissions from personal transport will use the National Travel Survey (DfT, 2006) data and London Transport Survey data (TfL, 2001) which avoids this as they are already regionally consistent (Appendix E). This is not necessarily the case for non-personal transport activity.

The allocation of emissions from business travel, freight and distribution is more contentious and the data available is substantially less detailed. Fixed point sources related to these activities (*eg.* fuel depots) are monitored by the EA and local authorities. Yet ideally these emissions should be allocated to the consuming region which is likely to increase the share of emissions allocated to London under current methods. However, it is of equal interest in policy terms to identify the contribution of different types of producer and service provider. Similar issues arise relating to travel by overseas visitors in London and by Londoners overseas and when allocating transport emissions from imports and exports. This topic is the subject of a more detailed scoping report.

The relationship between transport and land use at the urban scale can be explored through alteration of the network and travel time/cost/distance inputs into the landuse model. These will include the development of Crossrail, 2012 Olympic infrastructure *etc.* as and a finite number of pre-defined urban policy scenarios developed with stakeholders. Other city scale policies may include taxation, road-user charging, investment in local distribution and regulation. Some of these could also be implemented at a (supra-)national scale enabling the impact on London of imposing stricter policies on transport emissions to be explored. Likewise, the impact of assumed global advances in emissions reduction technologies (from the global socio-economic scenarios), fuel taxation and economic activity in the transport sector (from the economic modelling) will influence and/or constrain technological uptake (OST, 2005) and transport use in London.

Non-transport emissions

The non-transport emissions accounting tool enable users to explore the impact of different assumptions about energy demand, technology change and energy generation *etc.* CO_2 emissions can be counted from:

- Energy (electricity generation, gas and heating fuel consumption, population and sewage works *etc.*)
- Industrial processes,
- Waste emissions, and,
- Agriculture.

There are a number of tools already available for this purpose which are considered in Appendix F. Other emissions include non-CO_2 GHG emissions (*eg.* N_2O and CH_4) and indirect GHGs (*eg.* NO_x) where possible. Furthermore, heat emissions will be accounted for usage in the heat and health impacts module. Consequences in terms of emissions from changes to landuse, economic activity and population will be tracked. Stakeholders can explore the impact of landuse policies on emissions as well as a number of urban scale mitigation policies in relation to the quantity and type of energy consumed within each sector, and with respect to the supply side the mechanism and type of energy used in the generation of secondary fuels. Extra-urban policy would include global and/or national initiatives for GHG mitigation.

The emissions will be reported spatially at the ward level[‡‡]. Whilst point source emissions can be reported exactly, others may have to be disaggregated according to land use and/or some other measures of activity (*c.f.* Figure 2-3). Because the large number of wards combined with potential

‡‡ It may be inappropriate to present emissions estimates downscaled to ward levels under future land use scenarios due to the different types, and resolutions of analysis. This will be explored as the modelling activities are developed.

mitigation instruments that can be tested would lead to an intractable number of mitigation possibilities, the analysis will be at the city-scale and we do not propose to explore ward level mitigation directly.

Embedded energy

Embedded energy is the energy (and associated emissions) associated with the manufacture and distribution of products. These are predominantly industrial, construction and food products. This is an important component of urban footprint analysis. The embedded energy and emissions associated with activity in London are not considered in this research programme.

3.2.5 Impacts analysis

With the time and resources available it is not possible to develop impacts assessment modules for all the impacts listed in Section 1.3.2. Candidate modules have been selected based on the following pragmatic criteria:

- Relevance to stakeholders in London,
- Availability of expertise within project team,
- Potential for constructing adaptation and mitigation portfolios that can be managed and implemented on a city level.

The three primary modules are:

- River and coastal flood risk,
- Water resources, and,
- Heat and health.

Each of the models, and full range of input, output and policy variables, is described in more detail in Appendix C-I. The potential for implementing further modules is considered in Chapter 5. Some of the key features of each impacts module are now considered.

River and coastal flood risk

The aim of this impact assessment module is to investigate the flood risk in the tidal Thames Estuary (approximately between Kingston upon Thames and Southend). This module draws on extensive experience of broad scale flood risk analysis in the project team (Hall *et al.*, 2003, Dawson *et al.*, 2005, Dawson and Hall, 2006) and will seek to work closely with the ongoing Thames Estuary 2100 initiative which is developing a Flood Risk Management Plan for London and the Thames Estuary for the next 100 years. The module couples a stochastic model of storm surge and flow with a structural reliability analysis of flood defences, flood inundation simulations and a database of impacts location and damages.

The influence of changing precipitation and sea level can be explored. Risk management policy options that do not require additional hydrodynamic simulations, such as landuse changes, can be readily explored. However, only a limited number of adaptation options that seek to reduce flood risk through altering the hydrodynamic behaviour of the Thames Estuary can be tested. These include construction of new flood barriers, flood storage devices, managed retreat and channel modification. Where they generate significant emissions, infrastructure construction projects, and the operation of online barriers (this may become more frequent with increased sea level rise) can be input into the emissions accounting module.

Water resources

The aim of this impact assessment module is to investigate the water resource in the Thames Region *i.e.* the Thames catchment to Kingston upon Thames, which has a catchment area of 9948 km^2 (Figure 3-5).

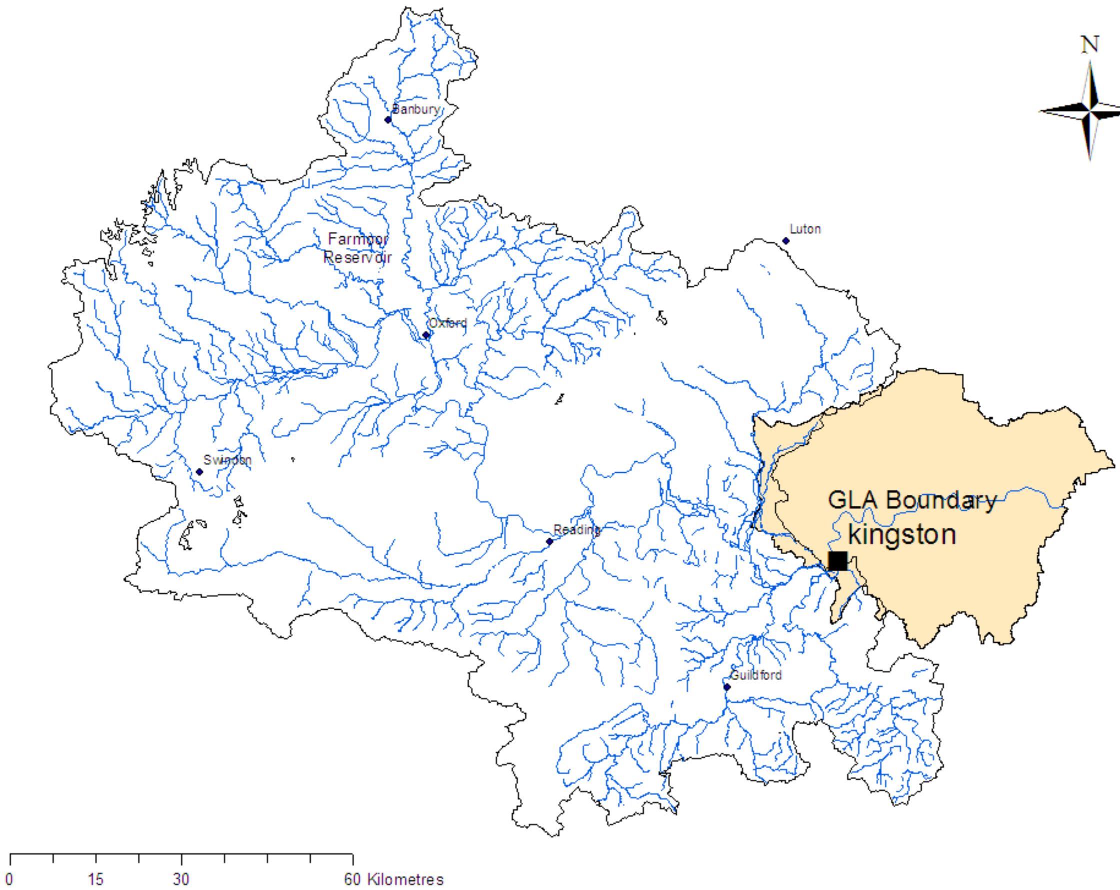

Figure 3-5 The river Thames catchment

A stochastic model that provides daily timeseries of rainfall and potential evapotranspiration for UKCIP (and other) climate scenarios (Kilsby *et al.*, 2006) will be used to evaluate changes to water availability and seasonality. In the first instance, the catchment is being modelled using the Environment Agency's conceptual rainfall runoff model: CATCHMOD (Wilby and Harris, 2006). Thames Water have been invited to participate with testing of new management strategies and scenarios for future operations using their existing water resource model: WARMS.

Changes to water demand, due to increasing population and changes to industry and building stock (from the landuse simulation model) or individual consumption habits (estimated in consultation with stakeholders) can be explored. Likewise, improvements to infrastructure such as reduced pipe leakage, a desalinisation plant, or the construction of a new reservoir (*eg.* as proposed at Abingdon) can also be explored. All these will be considered at a city/catchment scale (*i.e.* parameters such as pipe leakage, population demand, or storage capacity will not be spatially disaggregated). Infrastructure construction projects, and the operation of desalinisation plants provide inputs into the emissions accounting module.

<u>Heat and health</u>

The heat impacts model will have two tiers of analysis described in the following two sections, a high level analysis that looks at urban scale impacts only, and an intermediate level that considers mored detailed aspects of the built environment and land use.

This high level of analysis involves the correlation of heat emissions (from the emissions accounting modules) with temperature variables that have been downscaled to the urban area by correlating observations in London with climate model results. This will be intersected with information on population vulnerability (from the landuse model) and a heat vulnerability index (*eg.* GLA, 2006) to enable the impacts of heat on health to be explored under scenarios of socio-economic and climate change to be explored.

The ability to implement a more sophisticated level of analysis is due to a timely interaction with the EPSRC funded SCORCHIO project (2007-2010) which will develop a methodology for the analysis of the interaction between climate variables and urban form are considered by correlating urban landuse and morphology with heat emissions and measurements of the urban heat island. As with the high level approach, this can be intersected with information on population vulnerability to estimate the impacts of heat on health. Furthermore, this analysis enables the impact on the heat island of changes to urban landuse and the built environment to be explored. This methodology is in the early stages of development.

Construction emissions from alterations to morphology and landuse, and the operation of energy intensive devices such as air conditioning are inputs to the emissions accounting module.

3.2.6 Scenarios, behaviour and internal consistency

Under different global, national or local scenarios the attitude and behaviour of the population is assumed to be different. For example, under the SRES A group of scenarios one might expect a more consumerist scenario with more people owning cars, whilst the SRES B group may lead to better public transport infrastructure. Evidently, this will influence the development of the urban area. However, in this case these effects are captured through a number of factors. First, the ratio of economic activity in urban and rural areas for the SRES A scenarios will be higher than in the SRES B scenarios: the differences in activity will influence the urban land use model. Furthermore, the urban land use model must be parameterised to be consistent with the different scenarios. Considering the travel times/costs/distances networks: under the SRES B scenario group for example, improvements in public transport may be captured by alterations to the bus/train/underground networks – whilst under the A scenarios the road network may be a focus for investment. The influence of these different 'behaviours' is captured in the outputs of the landuse model, and their subsequent relationship with climate impacts and emissions can be tested.

Evidently, it is necessary to ensure there is 'internal consistency' in the scenarios, both in terms of the parameterisation of the models being used, and also in the responses available. For example, under the SRES A scenarios technological growth is expected to be more rapid, so the increased vehicle efficiencies that might be associated with these scenarios will not be available under SRES B scenarios. The UIAF will check for these consistencies and where appropriate warn the user from selecting certain mitigation or adaptation measures that are less likely to be compatible with the global socio-economic scenario.

3.2.7 Key model interactions

A summary of main linkages between the different components in the UIAF is shown in Table 3-1. A detailed overview of the linkages in this table and outlined above is shown in Figure J-1.

Table 3-1 Summary of variables passed between modules

		To						
		Economic	**Landuse**	**Transport emissions**	**Emissions**	**Flood**	**Water Resources**	**Heat**
From	**Exogenous variables from climate and socio-economic scenarios**	• Population • Exchange rates • Interest rates • GDP growth • Energy demand • Taxes • Government spending	• Population • Topography • Watercourses • Transport infrastructure	• Transport surveys: National & London Area • Vehicle use data • Vehicle stock data • Freight data • Usage forecasts • Emissions factors • Technology and vehicle efficiency	• Technology	• Topography • Flood defence infrastructure • Rainfall and storm surges	• Rainfall • Catchment properties • Water resource infrastructure • Population	• Temperature • Cloud cover • Wind • Humidity • Rainfall • Technology
	Economic	n/a	• Economic activity by sector	• Economic activity in transport sector	• Economic activity by sector	• Changing value of assets and hence flood damages	-	-
	Landuse	-	n/a	• Transport surveys: National & London Area	• Building stock & location • Population location	• Building stock & location • Population location • Transport network	• Building stock • Industry	• Building stock & location • Urban form • Population location • Transport network • Population vulnerability
	Transport emissions	-	• Potential changes to transport network, use/population behaviour and capacity	n/a	-	-	-	• Pollutants
	Emissions	-	-	-	n/a	-	-	• Pollutants
	Flood	-	-	-	• Energy intensive flood management activities	n/a	-	-
	Water Resources	-	-	-	• Energy intensive water resource activities	• Consistent river flow statistics	n/a	-
	Heat	-	-	-	• Energy intensive urban re-engineering activities	-	-	n/a

3.3 *User interface, visualisation and decision-support*

The UIAF will be implemented with a user interface frontend within a GIS. It is essential that this frontend is easily accessible in order to ensure successful application by stakeholders of the UIAF. A number of guiding principles for the construction of the interface have been identified in order to provide the most relevant information to decision-makers.

- Designed in consultation with key stakeholders and end-users.
- Several modes of operation, ranging from basic to expert user.
- Embedded within a GIS.
- Results will include spatially explicit impacts and emissions (where available) and timeseries plots.
- At the global scale the user will be able to select from a finite set of pre-defined and internationally established coupled climate and socio-economic scenarios.
- At the city-scale the user will be able to explore a set of pre-defined scenarios, including the business as usual and the London Plan
- At the city scale, the user will be able to fully customise a portfolio of adaptation and mitigation responses.
- Ability to compare scenarios against each other.
- Provision of advanced decision-support capability through uncertainty, sensitivity and robustness analyses.

3.3.1 Tiered interface

A key component of the UIAF frontend will be its tiered mode of operation, three different modes of operation are currently envisaged and their likely functionality are proposed in Table 3-2.

Table 3-2 Tiered modes of UIAF operation

Level	**Main user**	**Functionality**	**Interface**
Entry	First time users Stakeholders	Access to a limited number of pre-defined scenarios (eg. 'business as usual', London Plan).	Non-complicated wizard-based interface with the number of user defined options being constrained by lists.
Intermediate	Stakeholders interested in designing city-scale adaptation and mitigation portfolios	Customisation of development, adaptation and mitigation scenarios.	Drop down menus and parameter dials (or similar) used to define adaptation and mitigation options. Customise focus of interaction

			(*eg*. focus on emissions or impacts)
Advance	Researchers most likely to use in the first instance, but of interest to stakeholders keen to explore the use of uncertainty based decision-support tools	Uncertainty, sensitivity and robustness analysis of adaptation and mitigation portfolios. Reconfiguration of component modules and interactions.	User definition of uncertainty values and other expert controls. Manipulation mainly via command line interface

3.3.2 Testing a policy question

Policy questions will be tested by the user through a series of drop-down menus and textboxes. For example, if a user were to explore the impact of raising flood defence crest levels in 2030, a number of components of the UIAF are activated.

1) A coupled climate and socio-economic scenario is selected.
2) The variable 'crest height' and 'defence properties' are altered in the year 2030 to reflect rebuilding and crest raising of the flood defence system.
3) The resultant changes to defence failure probability, conditional on loading, are estimated.
4) The landuse change model provides changes to population and property, and consequently damages, over the 21st century based on the socio-economic scenario (**S** parameters).
5) Rising sea levels and altered precipitation patterns, downscaled from climate models, are used to recalculate joint loading probabilities.
6) The resultant flood risk is calculated by integrating the loading probabilities, defence failure probabilities and damages.
7) The flood risk is reported spatially and can be interrogated at decadal intervals over the 21st century.
8) Changes to emissions, due to construction or resultant use of online barriers are updated.

3.3.3 Uncertainty analysis

A key component of any modelling activity, more so in a situation which involves the coupling of several models, is to understand the uncertainties associated with the modelling process and how sensitive the model is to its input parameters. Uncertainty analysis involves systematic study of the sources and implications of uncertainty for decision-making. It helps to identify whether or not decisions are robust to uncertainty about what the future holds as wells as to methodological assumptions and expert judgements. It should be noted, however, that this does not involve ascribing uncertainties or probabilities to future scenarios or storylines, rather it is about gaining an improved understanding of the sensitivity of the models to the assumptions made in parameterising these scenarios.

A framework for uncertainty analysis has been proposed by Hall *et al.* (2006) and successfully piloted on the Thames Estuary (Dawson and Hall, 2006). Key features of this are shown in Figure 3-6 and summarised below. It is envisaged that these features of the UIAF will be incorporated into the advanced mode of operation of the UIAF. The user will have the ability to assign parameters probability distributions, interval bounds or other appropriate measures of uncertainty. These will be propagated through the UIAF model to provide estimates of uncertainty, model sensitivity and robustness in the climate impacts and emissions accounting results. As discussed below, these uncertainties may have implications for management decisions.

This development anticipates publication of the UKCIP08 probabilistic scenarios for the UK and associated increasing uptake of probabilistic methods for impacts and adaptation studies.

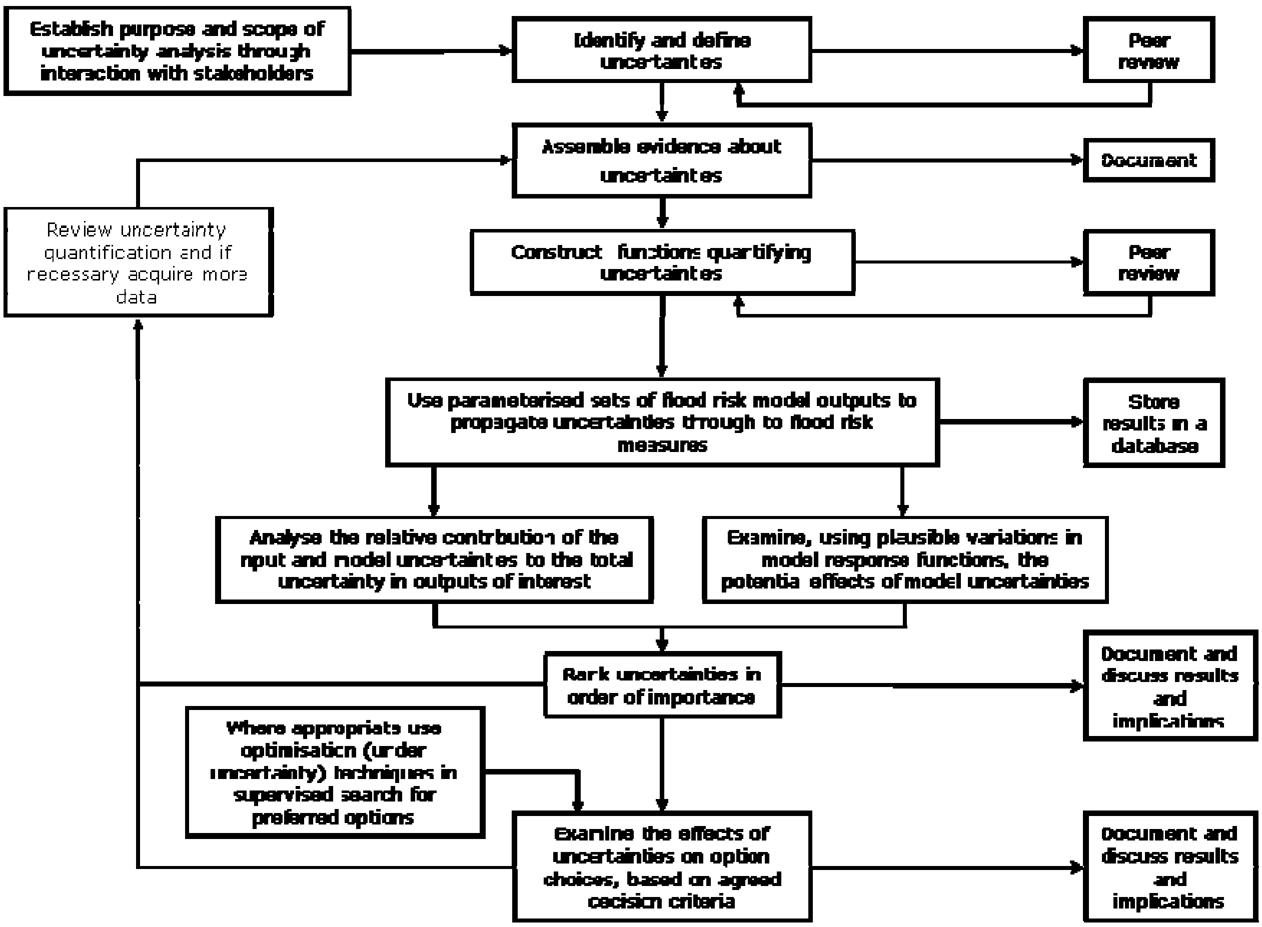

Figure 3-6 Uncertainty analysis framework (adapted from Hall et al., 2006)

Probabilistic analysis

The most widely accepted approach to quantified uncertainty analysis is to associate probability distributions to each of the uncertain variables that potentially influence the outcome of an analysis, in this case an analysis of risk and costs for a set of strategic options. Uncertainties about the change through time of key variables can be treated in the same probabilistic manner. The variance of probability distributions will be expected to increase further in the future.

Sensitivity analysis

Probabilistic analysis provides an impression of the overall uncertainty in how costs and risks might vary through time. Uncertainty-based sensitivity analysis develops quantified understanding of the contribution that input variables to an analysis, acting independently or in combination, make to uncertainty in output quantities of interest. Uncertainty-based sensitivity analysis provides a rational justification for investment in data collection or further studies.

The conventional way of addressing this sensitivity analysis problem is through 'one at a time' sensitivity analysis, where each individual variable is perturbed from its nominal value, while other variables are kept constant. This approach provides only a cursory impression of sensitivity as it does not test the range of potential variability and it does not deal with variations in combinations of variables. Variance-based sensitivity analysis overcomes both of these problems by testing the sensitivity of model output over the range of variability of each variable individually and in combination (Saltelli *et al.*, 2000).

Robustness analysis

The severity of the impact is influenced by the magnitude of climatic change, the rate of change, changes to variability and extremes as well as thresholds or non-linearities in the response of the Earth System. Consideration of severity, or the likely range of severities, is of importance when considering the range of adaptation options available as the most economically optimal adaptation option under expected conditions may not perform as well as other options when conditions diverge from the expectation.

Various notions of robustness have been proposed by government (DEFRA, 2005b) and in the literature (Rosenhead and Mingers, 2001). Here, the term 'robust' is used in the sense of a robust decision, which is a choice that continues to be desirable under a wide range of plausible future conditions. Robustness under uncertainty relates to the rate at which system performance declines when future conditions depart from expectations. A robust system will perform reasonably well even in situations which depart considerably from expectations. Robustness also provides a suggested metric for measuring the sustainability of projects (Evans *et al.*, 2004a, 2004b). There may be a trade-off between efficiency under assumed conditions and robustness.

Info-gap analysis (Ben-Haim, 2001) provides a quantified theory of robustness, and relies upon a minimum of information about the way in which a system may depart from expectations. It involves identifying the most critical one or two uncertainties in a decision and then exploring sensitivity of the decision variables to those uncertainties. Exhaustive searching is used to demonstrate how performance may deteriorate as conditions depart increasingly from expectations (Hine and Hall, 2006). Robustness analysis provides an alternative to conventional decisoin analysis for ranking alternative strategies. It provides a basis for constructing robust portfolios of management measures.

In an integrated assessment such as this, where the radically different options may appear to produce similar results, a robustness analysis can provide crucial information to support long-term planning across multiple sectors.

Decision analysis

Once decision-makers have taken reasonable measures to understand the implications of key uncertainties, and reduce them where it is feasible to do so, decision-makers should be able to proceed with making choices. They should do so:

- using risk-based approaches that incorporate the probabilities and consequences of the potential decision outcomes, and
- being mindful of severe uncertainties (which may manifest over extended timescales), and seek choices that are as far as possible robust to uncertainties.

The UIAF poses a multiple criteria problem in that a number of indicators and sectors are considered, each with a range of adaptation and mitigation problems. We are not pre-specifying an approach to multi-criteria multi-objective decision-making under uncertainty. The UIAF is however being established with a view to supporting uncertainty representation, as described above.

Chapter 4 Implementation plan

The timescale of the Cities programme is 3 years in total. The first six months or so have been a review which led to the first version of this working paper. The programme finishes on the 31st March 2009, and there will be a stakeholder launch event around this time. An abbreviated timetable for the Tyndall Centre Cities Research programme is shown in Figure 4-1. This shows the key dates, deliverables, events and work modules. The complete version of this timetable (disaggregated into smaller tasks) is shown in Appendix K.

The main phases of the research programme are to:

1) Perform a preliminary scoping review (this report),
2) Develop the component models of economics, land use and emissions accounting and climate impacts assessment,
3) Implement a preliminary demonstration of the UIAF that shows the impact on landuse and flood risk of a limited number of global and urban socio-economic scenarios,
4) Develop the UIAF by integrating the climate impacts and emissions accounting models,
5) Design, with stakeholders, and test portfolios of adaptation and mitigation options,
6) Write up findings in papers and a consolidated report for stakeholders and hold a stakeholder launch event.

Each model is expected to deliver one or more working papers (and subsequent journal papers). Further papers describing the results of the integrated assessment and stakeholder consultations will be produced. A consolidated stakeholder report will also be published.

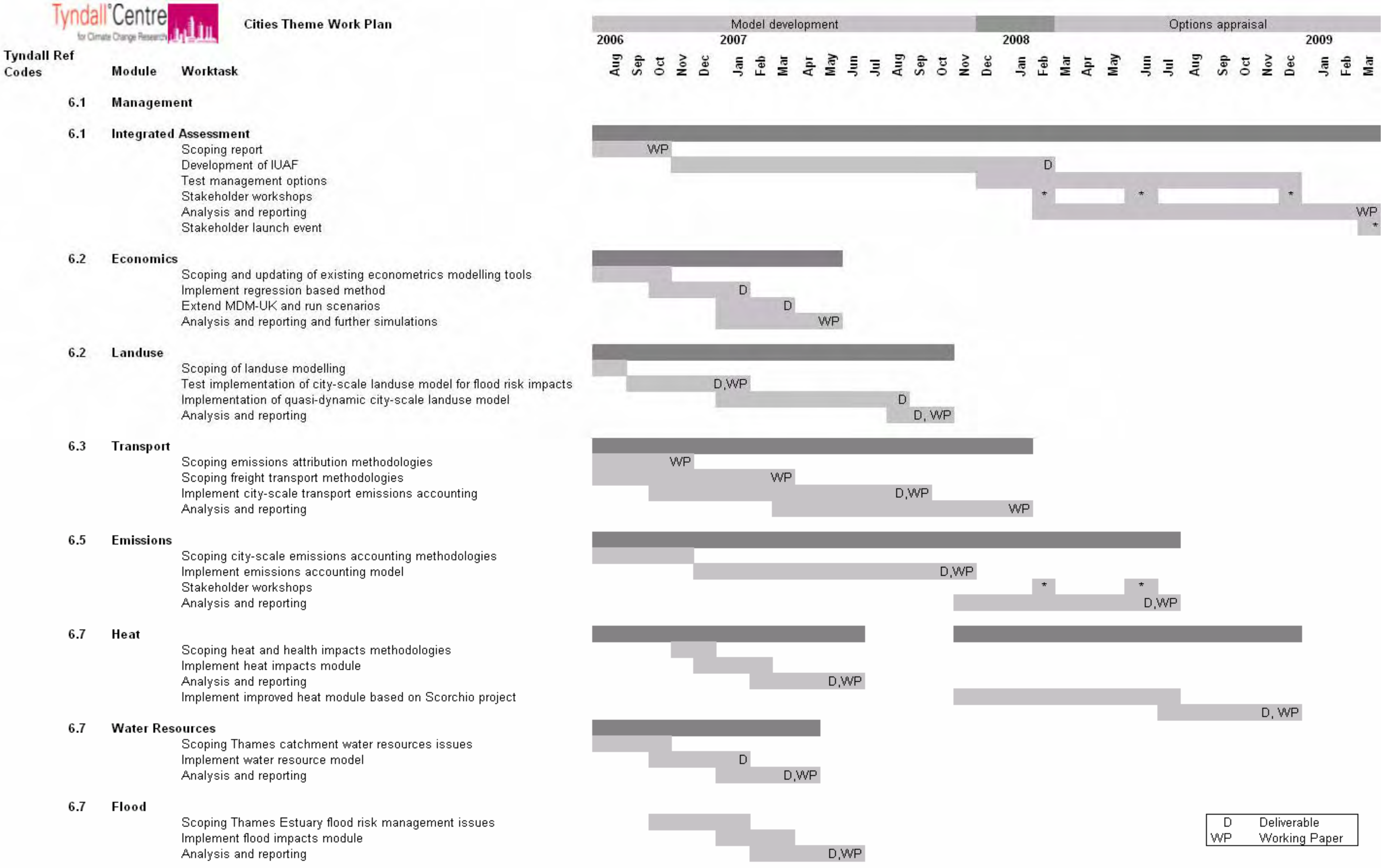

Figure 4-1 Timetable for Tyndall Centre Cities Research Programme

Chapter 5 Future directions

This chapter considers some of the limitations of this research programme as it currently stands and identifies areas for further work.

5.1 *IHDP Urbanisation research programme*

The IHDP urbanisation programme has a much broader remit than the Tyndall Cities programme as it seeks to provide a research framework for better understanding of the interactions and feedbacks between urbanisation and global environmental change. The programme has four research themes:

1) Urban processes that contribute to global environmental change,
2) Pathways through which global environmental change affects the urban system,
3) Interactions and responses within the urban system, and,
4) Consequences of interactions within urban systems on global environmental change.

Each of these themes identifies several areas for research. The Tyndall research programme addresses aspects of themes 1 and 2, although predominantly focuses on IHDP theme 3. However, it should be noted that the IHDP programme is not committed to providing deliverables, rather highlighting key areas of research that need to be addressed internationally. Future research and development needs to consider this programme.

5.2 *Impacts assessment*

The UIAF in its initial form will consider only three climate impacts modules. Whilst this presents a substantial amount of effort, obvious opportunities for further work will involve the development of additional impacts modules. For London, these could include:

- Urban flood risk,
- Air quality and health,
- Building and infrastructure subsidence and landslides,
- Wind storm,
- Water quality and health,
- Environmental impacts, and,
- Disease (although, as described in earlier sections of this report this is not expected to be a major problem in London over the 21st century).

The most obvious prioritisation of development effort would, in the first instance, be to tackle the stakeholder questions in Section 2.4 that the current research programme is unable to address.

However, development of some of these modules may require substantial research effort. For example, there is currently no efficient way of assessing the urban drainage flood risk at the urban scale, although recent methodological advances have identified promising research directions (Dawson *et al.*, 2006). Air quality is also a complex phenomenon to model and, much like urban drainage flooding, is influenced by interactions between flow and local features (*eg.* street canyons) and usually requires significant computational expense to resolve just one simulation. If more than a limited number of scenarios of adaptation and mitigation are to be explored, development of emulators (*c.f.* Mayer *et al.*, 2000) or statistical approaches may be necessary. For this, and other computationally demanding analysis, it will be necessary to address whether urban-scale modelling provides benefits in proportion to the limitations imposed by the additional computational expense.

5.3 *Model improvements*

A key principle of the UIAF is that it does not pre-determine the models used in the analysis. Future generations of the UIAF may benefit from improved data and/or modelling techniques. Development of more sophisticated models may also enable policy questions that can not currently be addressed, for example, testing the effectiveness of micro-scale adaptations aimed at changing transport use behaviour.

An initial development may be to increase the spatial resolution of some models, although care with this and other advances must be taken not to exceed the capability and accuracy of the available data.

The land use model may be extended to use other social simulation techniques such as automata or agent-based approaches which may be a more suitable approach for capturing population vulnerability and addressing some of the feedbacks identified in Section 5.4.

Improvements to the emissions accounting module should include consideration of embedded energy in food and manufactured goods. It could also explore the relationship between waste handling, recycling, processing, landfill processes and emissions. A dynamic approach, perhaps based on individual or agent-based modelling would provide a link between demand patterns, both from transport and non-transport emissions. Likewise, the implications of changes to the energy supply system such as increased deployment of decentralised and renewable energy should be explored in the context of the robustness of their reliability, particularly under changing climatic conditions.

5.4 *Feedbacks*

The UIAF as it currently stands does not consider the majority of feedbacks both within the urban area, and in the wider context of the Earth System.

The urban system is dynamic and adapts to both climate and socio-economic changes. These may occur in the form of short term ‘shocks’ such as a flood or introduction of a new tax, or long term ‘pressures’ such as sea level rise or climate change educational programmes. The response to these shocks and pressures manifests itself over different timescales and in different ways.

To improve understanding and simulation of long term socio-economic change in the urban area it is necessary to explore these feedbacks and understand:

- How climate shocks propagate through the economy,
- The long term impacts of extreme events,
- Do climate pressures naturally lead to behavioural change and to what extent can this be influenced to lead to ‘low emissions’ behavioural change,
- The impact of global and regional climate and socio-economic changes to natural, or other external (*eg.* imported goods from other countries) resources on which urban areas rely,
- Mechanisms for inducing behavioural change in individuals (*eg.* reducing energy consumption) and in the socio-economic landscape (*eg.* moving towards the hydrogen economy),
- The influence of climate change on the population (and different population groups), land use and development (responses to flood risk, increased urban temperatures *etc.*),
- The feedbacks between land use and the transportation network.

5.5 *Earth Systems Modelling*

Earth systems modelling (ESM) is a discipline that has grown from climate modelling that seeks to integrate the modelling of climate and biogeochemical cycles. At a global scale, the contribution of individual cities is seemingly negligible, however globally cities remain the major source of GHG emissions and these need to be incorporated into ESMs. Likewise, they are major drivers of interactions with other major biogeochemical cycles, for example, through mobilisation of heavy metals and pesticides. As with carbon, cities are sources of nitrogen emissions and interact with other major elemental cycles. Furthermore, they are indirectly responsible for the terraformation of other areas to provide resources for the city. In order to understand the broader interactions of the urban area with the Earth System, it is necessary to consider:

- the influence of urban form, function and values on a cities interaction with the processes that govern global climate and socio-economic change, and,
- the impact of changes in economic and land use in an urban area on biogeochemical and social systems outside the immediate boundaries.

Currently global and even regional ESMs operate at a resolution that is much coarser than the size of an individual city. Likewise, the number of processes that can currently be modelled within an ESM is still limited. It is therefore appropriate to consider urban areas in terms of their major inputs and outputs. However, as urban areas expand in size and reach and the sophistication of ESMs increases in terms of their resolution and the processes they model, it will become more important to consider the interaction of urbanisation and the wider earth system.

5.6 *Governance*

Increased engineering and technological resilience to climate change must be coupled with increased social resilience to reduce vulnerability to inevitable climate related events. At the urban scale a number of issues need to be explored. These include:

- Identification of features that make a governance system resilient,
- Considering how a resilient governance system may be created,
- How to deliver a flexible and integrated response to climate and socio-economic change at the urban scale,
- How to connect urban governance to national and local initiatives and organisations, and,
- How to build diversity into social, economic and ecological systems.

5.7 *The urban footprint and sustainability*

Evidently, London's global interaction extends far beyond its political boundary. In this programme we do not consider how changes in London impact on neighbouring regions in the UK or beyond. For example, the drop in industrial output has lead to reduced emissions in many Western countries, yet these countries still demand large quantities of manufactured goods – leading to emissions being displaced to other parts of the world, furthermore additional emissions generated from transporting these goods internationally. Significant advances have been made in the analysis of the urban footprint, are still highly uncertain and despite capturing vast amounts of information are still often incomplete (*c.f.* BFF, 2002). These studies are often not linked to the emissions, and other associated impacts.

Whilst understanding climate impacts and emissions are a crucial aspect of long term planning, it is essential to set this within the wider context of sustainability. The UK government has published guidance on sustainability metrics that quantify indicators relating to social justice and environmental quality (ONS and DEFRA, 2005), and further metrics to address whether interventions are able to account for future uncertainties such as robustness and precaution have been proposed by Evans *et al.*

(2004b). Further research should address further development of these sustainability metrics and in particular their relationship at the urban scale and the urban footprint. In particular it is necessary to consider how all this information is best used in the context of long term multi-criteria decision-making.

5.8 *Towards routine integrated urban assessment*

5.8.1 Integrated modelling

Any integrated assessment requires the coupling of multiple databases and models. Currently, this requires the 'patching' together of models in a bespoke manner which is a barrier to a longer term aim of more routine integrated urban assessment. Not least amongst the challenges are the software issues of integration and the commercial issues associated with modularity and standardisation. However, facilitating the connectivity of models and data should be considered in the wider context of stakeholder needs and decision-support. In particular it is necessary to design integrated modelling frameworks that are useful for constructing sets of simulations and outputs. Furthermore, decision-makers operate at a range of levels whilst natural and physical processes manifest themselves at a range of spatial and temporal scales demanding both a tiered and nested approach to modelling in which one can envision the integration of a range of low through high complexity models operating at a range of spatial and temporal scales.

5.8.2 Long term monitoring and data storage

Monitoring and measurements abstract information about a selection of system state variables. Significant benefits can be gained from the establishment of long term monitoring strategies. Vast amounts of data are (or can potentially be) collected on an urban area and the amount and quality of data is generally expanding as remote sensing techniques are becoming more accurate and densely deployed. Data is collected for a diverse set of economic, social, physical and natural aspects of the urban system. Consequently, this data is collected by a large number of different organisations and provided in a wide range of different formats. Moreover, this information is often collected at varying frequencies and resolutions. Evidently, there is a need for a more structured approach to monitoring and data storage at the urban scale. In the US, and more recently a single project in the EU, has gained significant insights into ecological systems through a Long-Term Ecological Research (LTER) programme. A similar (perhaps Long-Term Urban Research - LTUR?) programme focussing on urban areas could provide a data repository and hub for case studies into urban research. The existence of several sites that monitor and model a wide range of urban areas would provide additional value to the understanding of urban areas.

5.9 *Beyond London*

The application of this UIAF to London represents a substantial research challenge, however other cities will present formidable and often different challenges. The transferability of the generic UIAF and some of the potential challenges for actual implementation are now considered.

5.9.1 UK cities and/or regions

The London implementation of the UIAF is based on national datasets (such as the Office of National Statistics or Department of Transport *etc.*) and is not reliant on data only collected for London. Likewise, the UK is a relatively small island nation and therefore the most significant impacts of climate change tend to be common throughout (flooding, water resources *etc.*). Therefore the UIAF as it is implemented in London should be reasonably transferable. However, there are two main challenges for implementing the UIAF in other UK cities.

1) London is considered a region of the UK and is modelled as a separate unit within the economics module used in this implementation. Other cities are considered to be parts of regions and therefore, either an alternative model, or a downscaling relationship between the city and the regional economy is needed.
2) The landuse, impacts and emissions modules will need to be set up and calibrated for each city analysed.

5.9.2 Beyond the UK

An implementation of the UIAF on cities outside of the UK is likely to pose more substantial research challenges.

1) Cities have different headline climate impacts and priorities. For example, cities in warmer climates may consider disease may be a higher priority impact assessment module than in the UK.
2) Each country has a system of governance, cultural values and socio-economic profile that is unique. As in London, contact with local stakeholders is essential before any similar city-scale assessment can be achieved.
3) Developing world cities are often growing at a much greater rate and are subsequently trickier to model due to the rapid changes taking place. Many rapidly growing cities are characterised by unauthorised development and the existence of large scale slums – frequently with unknown population and landuse.
4) Despite the major uncertainties inherent in this type of modelling and the nature of much of the data used in the London UIAF implementation, the UK is relatively data-rich. Other locations may not have the same density, or type of information available and will require

alternative modelling approaches. This may require a greater emphasis on the use of remote sensing technologies to parameterise models, and appropriate consideration of the uncertainties introduced as a result of increased data-scarcity.

Chapter 6 Summary

The objectives of this report, as identified in Chapter 1, are now reviewed.

1) Introduce the Tyndall Centre Cities Programme and outline its aims and objectives.

The Tyndall Centre Cities Programme has been introduced in Chapter 1. The aim of the programme is to develop a city-scale assessment capacity that simulates the evolution of climate impacts and emissions over the 21st century. This city-scale assessment tool will be applied by urban policy-makers, planners, engineers and other stakeholders to compare alternative adaptation and mitigation strategies and to consider *how cities grow whilst reducing emissions and vulnerability to climate change*.

2) Review the key impacts on cities from global and climatic change and how comparable and related projects have attempted to address these issues.

The key impacts of climate change on cities are considered in Chapter 1. More specific consideration of the impact of climate and socio-economic change on London, the Tyndall Cities Programme case study is given in Chapter 2. An ongoing review of other studies on climate change in cities is in Appendix A. The high concentration of people and economic activity makes cities potential hotspots of climate vulnerability. Potential climate impacts can have a direct impact on the city such as flooding, drought, heatwaves *etc.* whilst others, such as changes to available agricultural resources are less direct. Meanwhile, cities are also major emitters of greenhouse gases both directly (*eg.* heating, electricity use) and indirectly (*eg.* embedded carbon in manufactured and agricultural goods). Adaptation to climate change can often induce energy-intensive adaptations, such as air conditioning or desalinisation, that undermine emissions reduction efforts.

3) Report on the findings of the stakeholder review of key policy issues for London.

The ongoing review of stakeholder policy questions and priorities is reported in Chapter 2. A number of policy questions have been identified, and those which can be addressed in this research programme have been identified. These include exploring the effectiveness of:

- economic instruments such as taxation and emissions trading,
- development regulation,
- transport regulation and emissions charging,
- increasing energy efficiency through retrofitting buildings or deploying improved technology, and,

- infrastructure projects such as new reservoirs, raised flood defences *etc*.

4) Describe the city-scale integrated assessment framework both in generic terms to demonstrate how the approach may be transferred between cities and in detail describing exactly how it is being implemented for London.

The Urban Integrated Assessment Framework (UIAF) is described in Chapter 3 and in more detail in Appendices C-I. The integrated assessment framework is unique in that it:

- integrates quantitative evaluations of climate impacts and emissions at an urban scale,
- is driven by scenarios of global climate and socio-economic change over the 21^{st} century,
- explores the interaction between land use, climate impacts and emissions, and,
- involves the analysis of both adaptation and mitigation options in a unified framework.

The UIAF is in the first instance presented in a generic form which is not constrained to application on a specific case study site, or the use of specific socio-economic, landuse, climate impacts and emissions accounting modules. More detailed consideration of the application to the case study site, London, is also given in Chapter 3. A timescale for implementation is given in Chapter 4

5) Identify areas for future development.

Limitations and areas for future development are identified in Chapter 5. Key areas for future research and development are:

- Additional impacts assessment modules,
- Analysis of broader urban footprint issues and embedded energy and emissions,
- Consideration of feedbacks between climate impacts, transport, landuse change and economy,
- How urban areas can be better represented in Earth Systems Modelling, and,
- Issues likely to arise from implementing a similar UIAF in other cities – in particular cities undergoing rapid change or with scarce data.

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Appendix A: Related initiatives

There are a number of relevant initiatives being undertaken in the UK, EU and internationally that are briefly summarised below (more information will be provided in subsequent versions of this report on each of the projects or programmes listed). This review is ongoing and suggestions for projects to include are invited.

Project or Programme	Brief description
ADAM (Adaptation and Mitigation Strategies)	The ADAM project aims to: • assess the extent to which existing and evolving EU (and world) mitigation and adaptation policies can achieve a tolerable transition to a world with a global climate no warmer than 2°C above pre-industrial levels, and to identify their associated costs and effectiveness. • develop and appraise a portfolio of longer term policy options that could contribute to addressing shortfalls both between existing mitigation policies and the achievement of the EU's 2°C target, and between existing adaptation policy development and EU goals and targets for adaptation. • develop a novel Policy-options Appraisal Framework and apply it both to existing and evolving climate policies, and to new, long-term policy options in the following four case studies: European and international climate protection strategy in post-2012 Kyoto negotiations; a re-structuring of International Development Assistance; the EU electricity sector and regional spatial planning.
Alliance for Climate Protection	Al Gore's campaign that aims to: • Motivate a critical mass of the public and influential constituencies to demand strong and just action to cut U.S. emissions and to make solving global warming a national political imperative. • Implement solutions to global warming that cap and cut U.S. global warming pollution emissions in the near term, setting a framework and trajectory to reduce emissions by more than half by mid-century. • Develop a political consensus for further international

	agreements that includes full participation by developing economies in achieving emission reduction targets.
APRIL (Air Pollution Research In London)	The APRIL network brings together the research community and those responsible for air quality management to establish priorities for research, and to collaborate in fulfilling these research needs. It was established with funding from the Engineering and Physical Sciences Research Council (EPSRC) and is supported by the Mayor of London, Environment Agency, DEFRA and London boroughs. Its activities encompass research on measurements of atmospheric concentrations of pollutants, meteorology, emissions and modelling of atmospheric dispersion and atmospheric chemistry, impacts of air pollution on human health and on London's flora and fauna, indoor air pollution, assessment of abatement strategies, and the social and economic aspects of air quality management.
ASCCUE (Adaptation Strategies for Climate Change in the Urban Environment)	ASSCUE is one of six projects funded by the EPSRC BKCC programme. It is considered separately because of its direct relevance to this research project. The project examines the consequences of climate change for buildings, urban greenspace, and human comfort and develop and test appropriate adaptation strategies. The project is reported in several journal papers[12]. The analysis is implemented at urban and sub-urban scales and provides qualitative measures of risk for 'morphological units' under a limited number of UK climate and socio-economic scenarios.
C20 (Large Cities Climate Leadership Group)	A group of cities committed to the reduction of urban carbon emissions and adapting to climate change. It was founded following the World Cities Leadership Climate Change Summit organised by the Mayor of London in October 2005.
CAP-LETR (Central-Arizona Phoenix Long Term Ecological Research programme)	The CAP LTER project is one of 24 long-term sites funded by the National Science Foundation (NSF). LTER sites have tended to focus upon pristine locations well removed from the myriad effects

[12] Gwilliam, J., Fedeski, M., Lindley, S., Theuray, N. and Handley, J. (2006) Methods for assessing the risks from climate hazards in urban areas, *Proc ICE Municipal Engineer*, 159(ME4), 245-255.
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	brought about by extensive human modification and dominance of ecosystems. The CAP LTER site provides a unique addition to the LTER research by focusing on an arid-land ecosystem profoundly influenced, even defined, by the presence and activities of humans and is one of only two sites that specifically studies the ecology of urban systems. Biological, physical, and social scientists from Arizona State University and a wide range of local partners are working together to study the structure and function of the urban ecosystem, assess the effects of urban development on the Sonoran Desert, and define the impact of ecological conditions on urban development.
Carbon Vision Buildings Programme	Carbon Trust and EPSRC Thematic Programme (with NERC and ESRC support) that seeks to stimulate a step change in thinking that will radically improve the way the world thinks about this new era. The various university consortia supported by Carbon Vision bring together expertise from many disciplines and enables the Carbon Vision partnership to develop unique research programmes that explore how to devise low carbon options for the future in the building, industrial and power generation sectors.
CATSIM (Catastrophe Simulation)	A model developed by IIASA (Austria) to assess the financial vulnerability of the public sector to extreme events in hazard-prone countries and to illustrate the tradeoffs and choices a country government must make in managing the economic risks due to natural hazards.
Cities Revealed	Commercial datasets owned by The GeoInformation Group of high resolution remote sensing datasets.
Climate Alliance	The Climate Alliance is an association of European cities and municipalities that have entered into a partnership with indigenous rainforest peoples. The aim of the Climate Alliance is to preserve the global climate. In our view, this involves reducing greenhouse gas emissions to a sustainable level in the industrialized countries of the north, and conserving the rainforests in the south of the planet.
COMPETE	INTERREG IIIC funded project extending the Core Cities Group

	into Europe (http://www.compete-eu.org/)
Core cities	The group of cities that represents England's largest city-regions that aims to promote their role as drivers of regional and national economic growth. The cities are Birmingham; Bristol; Leeds; Liverpool; Manchester; Newcastle; Nottingham and Sheffield. (http://www.corecities.com/).
Davos Climate Alliance	An Initiative of the World Economic Forum to promote sound measures and best practice aimed at mitigating carbon related risks. The main objectives are to raise awareness about the issue of climate change among decision makers and to motivate those in the private sector to approach the climate change issue in a constructive way.
Decision Centre for a Desert City (DCDC)	DCDC's research establishes relationships between climatic conditions and water decision making and is organized around three sets of research questions (i) what are the sources of regional climate variation and change, and how do they influence water supply and demand, (ii) how do humans—operating as individuals, households, and communities—make decisions about this resource, and (iiI) what climatic conditions and human decisions put which people and what places at most risk from climate—induced water scarcity? Longer-term modeling efforts will integrate knowledge across these sets of research questions and produce alternative visions of the region's future (http://dcdc.asu.edu/).
Earth Institute at Columbia Institute	The Earth Institute has two relevant programmes: 'Urbanisation' and 'Climate & Society'. The urbanisation theme is looking both at sustainability and hazards and risks, with the main case study in New York. The climate and society theme is looking at the interaction between climate change and social processes (both in time and space), sustainability and the role of stakeholders.
EPSRC Quantifiable Cities	The EPSRC Quantifiable City project addresses urban sustainability issues, particularly common property problems which have complex origins, many possible solutions, and hence are often the most difficulty to solve. The latest phase has extended the decision support system to model air quality through integration of

	a mobile and stationary source emission inventory and a dispersion model in order to investigate transport management within the context of the National Air Quality Strategy Plan. A disease model has also been developed to allow investigation of the impact of transport emissions on respiratory disease incidence. Additional model developments are continuing in the areas of water and energy use, wastewater and stormwater management, with further work to address land-use transport interaction, noise and a detailed respiratory disease burden assessment.
EPSRC Sustainable Urban Environment	A research programme targeted at urban sustainability. The first round of SUE supported 12 projects addressing: Urban and Built Environment; Waste, Water and Land Management; Transport; Metrics, Knowledge Management and Decision Making.
EPSRC Building Knowledge for Climate Change (BKCC)	BKCC is a portfolio of research projects looking at how climate change will affect aspects of the built environment. The ASCCUE project is one of the BKCC projects. BKCC research projects cover areas ranging from risk management to the impact of climate change on energy supplies, land use, urban drainage and historic buildings.
EPSRC Sustaining Knowledge for Climate Change (SKCC)	SKCC will preserve and extend the community of researchers and end users assembled for BKCC. The aims of the SKCC are to sustain the researcher and end user community assembled around the BKCC programme, to synthesise and disseminate results from BKCC in order to maximise impact and to develop a coherent user-led plan for future research into the impacts of climate change on the built environment and infrastructure and development of adaptation solutions.
European Spatial Planning: Adapting to Climate Events (ESPACE)	A project that aims to promote awareness of the importance of adapting to climate change and to recommend that it is incorporated within spatial planning mechanisms at local, regional, national and European levels. Focussing on North West Europe, ESPACE will look at how we manage our water resources and plan for a future with a changing climate.
Greater Phoenix (GP2100)	The Greater Phoenix 2100 project aims to provide information

	that describes the 100-year regional implications of the decisions being contemplated today. Greater Phoenix 2100, initiated by Arizona State University (ASU), wants the best possible scientific and technical information to be of use in making knowledge-based decisions that will shape the region during the next 100 years. Greater Phoenix 2100 hopes to develop regional tools and sponsor events to provide that knowledge. The project has partnered with local and state governments, community organizations, and private businesses.
ICLEI (Local Government's for Sustainability)	An international association of local governments and national and regional local government organizations that have made a commitment to sustainable development. More than 475 cities, towns, counties, and their associations worldwide comprise ICLEI's growing membership. ICLEI works with these and hundreds of other local governments through international performance-based, results-oriented campaigns and programs.
International Human Dimensions Programme (Urbanisation)	The International Human Dimensions Programme on Global Environmental Change is an international, interdisciplinary science programme dedicted to promoting, catalyzing and coordinating research on the human dimensiaons of global environmental change. IHDP takes a social science perspective on global change and it works at the interface between science and practice. The specific focus of the Urbanization Project will be on understanding the nature of the interactions between global environmental change and urban processes, the direction, rate, intensity and scale of these processes as well as the challenge of global environmental change to the functioning, stability and sustainability of urban areas. The research foci are (i) urban processes that contribute to global environmental change, (ii) pathways through which global environmental change affects the urban system, (iii) interactions and responses within the urban system and (iv) consequences of interactions within urban systems on global environmental change (http://www.ihdp.uni-bonn.de/).
ISCAM (Integrated Sustainable Cities Assessment Method)	ISCAM is a flexible toolkit for sustainability analysis and appraisal in any city or region. Its foundation is an 'integrated assessment'

	mapping method which links environmental, social and economic issues. This combines with purpose-designed software in a very usable and transparent environment-economy scenario accounting model, which helps to map out scenarios, indicators, targets, and 'trend to target' assessments. ISCAM is also being applied to futures workshop exercises and indicators programmes for national and regional bodies. The 'integrated assessment' perspective can also be focused on the challenge of sustainability appraisal for regional planning and management. The new regional institutions have an urgent need for joined-up policy-making, in the midst of complexity and uncertainty. Appraisal methods and tools for land-use, economic and infrastructure planning are being developed, going beyond policy 'tick-lists' to innovative but technically grounded appraisals of problems and prospects. ISCAM also has strong linkages with economic appraisal and environmental or ecological economics. These are being explored in a project, 'Integrated Assessment & Economic Analysis of Sustainable Development in a City-Region', funded by the Global Environmental Change programme of the Economic and Social Research Council'
Klimaat voor ruimte (Climate change spatial planning)	A programme managed from Amsterdam and Wageningen Universities in The Netherlands that aims to face the challenges of living in a changing climate by providing sectors involved in spatial planning a sound scientific base in a participatory way. The programme is expanding to look at urban areas. (http://www.klimaatvoorruimte.nl/)
Land Use Transport Research Cluster	The LUTR cluster links several different projects in the area of sustainable urban mobility, including land use, transportation, and the environment. The common objective is to develop strategic approaches and methodologies in urban planning that all contribute to the promotion of sustainable urban development. This includes issues of transportation demands and related land use planning, the design and provision of efficient and innovative transportation services including alternative means of transportation, and the minimisation of negative environmental

	and socio-economic impacts.
Methodology for Assessment of Transport Impacts of Social Exclusion (MATISSE)	MATISSE aims to develop and apply Integrated Sustainability Assessment of EU policies. The key objective of the project is to compile and validate an evaluation tool to assess the impact of transport-related policy interventions on social exclusion.
OTHERS	
REAP	Resource Accounting for Sustainable Consumption and Production in the UK. Developing and implementing modelling approaches to understand the material flows, carbon dioxide emissions.
Regional Climate Change Impact and Response Studies in East Anglia and North West England (RegIS, and RegIS 2)	The objectives of the RegIS projects are: • To assess the impacts of future climate change on the agriculture, biodiversity, hydrology and coasts of East Anglia and the North West of England; • To explore the impacts for the 2050s; • To involve regional experts, decision-makers and other 'stakeholders' in the design of the assessment, for example through the identification of critical impacts, interactions and adaptive responses; • To compile a geographically-referenced database for the North West and East Anglian regions including environmental data, climate change scenarios and socio-economic change scenarios; • To adapt, calibrate and validate existing models of agriculture, water resources, biodiversity and coastal zones for East Anglia and the North West, which can be used to assess the impacts of climate change. • To analyse the range of possible adaptive responses and the influence of future policy and socio-economic scenarios upon the response. • To work with stakeholders to communicate the findings to the appropriate policy and lay audiences. • To produce a methodology which can be used by other stakeholders and similar interest groups to address the same kinds of questions elsewhere in the UK.

Transims (Los Alamos National Laboratory)	TRANSIMS is an agent-based simulation system capable of simulating the second-by-second movements of every person and every vehicle through the transportation network of a large metropolitan area. It consists of mutually supporting simulations, models, and databases. By employing advanced computational and analytical techniques, it creates an integrated environment for regional transportation system analysis. TRANSIMS is designed to give transportation planners information on: traffic impacts, energy consumption, traffic congestion, land use planning, traffic safety, intelligent vehicle efficiencies, and, emergency evacuation (http://transims.tsasa.lanl.gov/)
UNEP/WHO Air pollution in the Megacities of Asia (APMA)	More than half of the world's population live in urban areas in Asia. Urban air pollution in most Asian Megacities (with a population of more than ten million) such as Beijing, Delhi and Jakarta has worsened due to the cumulative effects of population growth, industrialisation and increased vehicle use with resultant considerable health consequences. The APMA project will: • collate available data on emissions of urban air pollutants from fixed and mobile sources, trends in urban air pollutant concentrations, and existing studies on health and environmental impacts of urban air pollution in order to facilitate information exchange between Megacities in the project; • identify and review existing goals, policies and strategies in urban air pollution management at the local, provincial and national levels; • identify best practice in urban air pollution management in selected European cities and to determine the relevance of the European experience of urban air pollution management to Asian Megacities; • make recommendations to reduce urban air pollution in the form of a regional action plan; and • promote regional cooperation in the management of air pollution in Asian megacities via establishment of a network. • to facilitate the introduction of regional guide-lines on urban air pollution management in Asia via regional action plans.

UrbanSim (University of Washington)	UrbanSim is a software-based simulation model for integrated planning and analysis of urban development, incorporating the interactions between land use, transportation, and public policy. It is intended for use by Metropolitan Planning Organizations and others needing to interface existing travel models with new land use forecasting and analysis capabilities. The software enables metropolitan planning organizations and others to forecast the likely effects of land use and transportation plans and policies by taking into account environmental, sociological, and economic dimensions.
VivaCity 2020	An EPSRC funded research initiative that aims to deliver practical tools and resources to support sustainable and socially responsible urban design decision-making. VivaCity2020 is analysing urban planning, design and consultation processes to identify when and how key decisions related to urban sustainability are made. The processes are being mapped, and a support specification formulated for the development of tools and resources to enable widened stakeholder participation (http://www.vivacity2020.eu/).

Appendix B: Glossary and modelling terminology

B.1 Acronyms

Acronym	Explanation
ABI	Association of British Insurers
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DCLG	Department of Communities and Local Government
DEFRA	Department of the Environment, Food and Rural Affairs
DoH	Department of Health
DfT	Department for Transport
DTi	Department of Trade and Industry
EA	Environment Agency
EU	European Union
GCM	General (or Global) Circulation (or Climate) Model
GIS	Geographical Information System
GLA	Greater London Authority
GOL	Government Office for London
GVA	Gross Value Added
IHDP	International Human Dimensions Programme
IMD	Index of Multiple Deprivation (DEFRA dataset)
IPCC	Intergovernmental Panel on Climate Change
LAEI	London Atmospheric Emissions Inventory
LATS	London Area Transport Survey
LAU	Local Administrative Units
LDA	Local Development Agency
LCCA	London Climate Change Agency
LCCP	London Climate Change Partnership
LSx	London Sustainability Exchange
MDM-UK	Multisectoral Dynamic Model of the UK
NAEI	National Atmospheric Emissions Inventory
NLUD	National Land Use Database
NO_x	Nitrogen oxides

NTS	National Transport Survey
NUTS	Nomenclature of Units for Territorial Statistics
O_3	Ozone
ODPM	Office of the Deputy Prime Minister (replaced by DCLG)
ONS	Office for National Statistics
PET	Potential Evapo-Transpiration
PM_{10}	Particulate matter of up to 10 micrometers in diameter
RCM	Regional Circulation (or Climate) Model
REEIO	Regional Economy-Environment Input-Output model
SO_x	Sulphur oxides
SRES	Special Report on Emission Scenarios (IPCC emissions scenarios report)
TfL	Transport for London
TG	Thames Gateway
TW	Thames Water
UHI	Urban Heat Island
UIAF	Urban Integrated Assessment Framework
UK	United Kingdoms of Great Britain and Northern Ireland
UKCIP	UK Climate Impacts Programme

B.2 Model parameterisation

A generic model has the form $\mathbf{y}=f(\mathbf{x})$ where $\mathbf{x}$ is the multi-dimensional array of input variables and $\mathbf{y}$ is the multi-dimensional array of output variables. Here it is useful to consider components of the IUAF to be a function of four types of basic variable, taking the form $\mathbf{Y}=f(\mathbf{X},\mathbf{S}, \mathbf{P}, \mathbf{B})$ where:

- $\mathbf{Y}:=\{x_1,x_2,\ldots,x_n\}$ are the model output parameters,
- $\mathbf{X}:=\{x_1,x_2,\ldots,x_n\}$ are basic model initialisation/calibration parameters,
- $\mathbf{S}:=\{s_1,s_2,\ldots,s_n\}$ are non-urban scenario parameters which are changed to explore a limited number of scenarios of conditions broadly outside the control of city-scale planners and managers *eg.* global/national economy, demography, technology *etc.*,
- $\mathbf{P}:=\{p_1,p_2,\ldots,p_n\}$ are urban policy parameters which are variables that a city-scale decision maker might hope to influence *eg.* land use, technology uptake, infrastructure, transport behaviour *etc.*,
- $\mathbf{B}:=\{b_1,b_2,\ldots,b_n\}$ are parameters that measure the effectiveness of policy variables on changing behaviour.

For example for a flood risk model:

- **Y** contains spatially and temporally variable measures of flood risk,

- **X** contains the variables which are needed to initialise and calibrate the flood risk model and include descriptions of the present condition of the flood defence system, the present distribution of tide levels, the present land use in the floodplain *etc.*,
- **S** contains parameters such as sea level rise scenarios, changes in household wealth *etc.*,
- **P** contains parameters that flood risk managers might hope to have some control over and will wish to test in the models such as land use regulation, flood defence level *etc.*,
- **B** contains parameters that measures the ‘strength’ of a particular policy instrument on changing behaviour, such as the effectiveness of education programmes at raising awareness (and hence reduce flood risk) to flooding.

Generally, the integrated assessment model user will have a limited selection of combinations of S, but be able to explore a much wider parameter space of P (although the infinite permutations of some parameters such as configuration of the transport network will mean that only a limited, but carefully chosen, selection will be explored). However, it will be necessary, in consultation with stakeholders to limit the space of policy parameters to a manageable number required to address key policy questions.

Appendix C: Economic modelling

C.1.1 Economic modelling sectors

There are forty-one economic sectors in the model:

1) Agriculture,
2) Coal, oil & gas extraction,
3) Non-energy mining,
4) Food, drink & tobacco,
5) Textiles, cloth & footwear,
6) Wood & paper,
7) Printing & publishing,
8) Manufactured fuels,
9) Pharmaceuticals,
10) Chemicals,
11) Rubber & plastics,
12) Non-metallic mining processes,
13) Basic metals,
14) Metal products,
15) Machinery,
16) Electronics,
17) Electrical & instruments,
18) Motor vehicles,
19) Other transport equipment,
20) Other manufactures,
21) Electricity,
22) Gas manufacture & distribution,
23) Water supply,
24) Construction,
25) Wholesale trade,
26) Retail trade,
27) Hotels & restaurants,
28) Land transport,
29) Water transport,
30) Air transport,
31) Communication,

32) Banking & finance,
33) Insurance,
34) Computing services,
35) Professional services,
36) Other business services,
37) Public administration & defence,
38) Education,
39) Health & social work,
40) Other market services, and,
41) Unallocated.

C.2 Methodological description

The MDM and the E3 models have been developed by Cambridge Econometrics over many years. They are coupled Environment-Energy-Economy models designed for long term economic analysis (Figure C-1). The model is based on Keynsian macro-economics: contrary to many economic models MDM/E3 assumes the market is *not* always in equilibrium. The governing equation of the model is that:

$$\text{Demand} = \text{Internal demand} + \text{Investment} + \text{government spending} + \text{exports} - \text{imports} \tag{C.1}$$

'Internal demand' is established by "Input-Output" relationships between sectors. For example, how many units of Sector B-Z are needed to produce a Unit of Sector A. The effect of major economic change can be explored by updating these Input-Output relationships, for example, through the use of a Kondratiev wave.

The overall objective is to provide output tables of economic activity (measured in terms of economic value added; the monetary value of an entity at the end of an time period minus the monetary value of that same entity at the beginning of that time period) as input to the land use and population distribution model, the transport emissions accounting model and the energy use emissions accounting model.

There are two models available that are relevant:

- MDM is a UK model that provides the necessary data for GL to 2020 in annual steps.
- E3MG is a global model with the UK separately identified, and the same industrial sectoral structure, but it runs to 2100.

MDM-UK has three main advantages over E3MG:

1. It is already developed and has a well respected baseline scenario.
2. London is defined as a separate output area.
3. GLA are familiar with its outputs, as these are used as inputs to the REEIO model, developed for the GLA as well as other regional models by Cambridge Econometrics.

However, as part of the research programme, MDM-UK will be extended to model until 2100. Likewise, the data produced from global socio-economic scenarios is often only reported at a global or European level (*i.e.* the UK is not reported as a separate region). Therefore a downscaling approach will be implanted that establishes the relationship (or a range of likely relationships) between global and UK parameters. A full review of global, UK and London socio-economic scenarios is currently under way which will be used:

1. as part of the evidence for developing your downscaling methodology from Global to UK socio-economic scenarios,
2. as evidence for the baseline parameterisation of MDM2100,
3. development of alternative scenarios (*eg.* mitigation scenarios) for use in MDM2100, and,
4. as a report and Tyndall working paper that can be referenced by the rest of the project team as the core 'scenarios' document in the Cities theme.

Implementation of the MDM-UK model will mean that only a finite number of pre-selected economic scenarios can be considered. However extension of the MDM-UK model to 2100 enables the impact of structural changes to the economy to be explored (*c.f.* Köhler, 2003). The structure of the model is shown in Figure C-1 and its relationship with the UIAF is shown in Figure C-2.

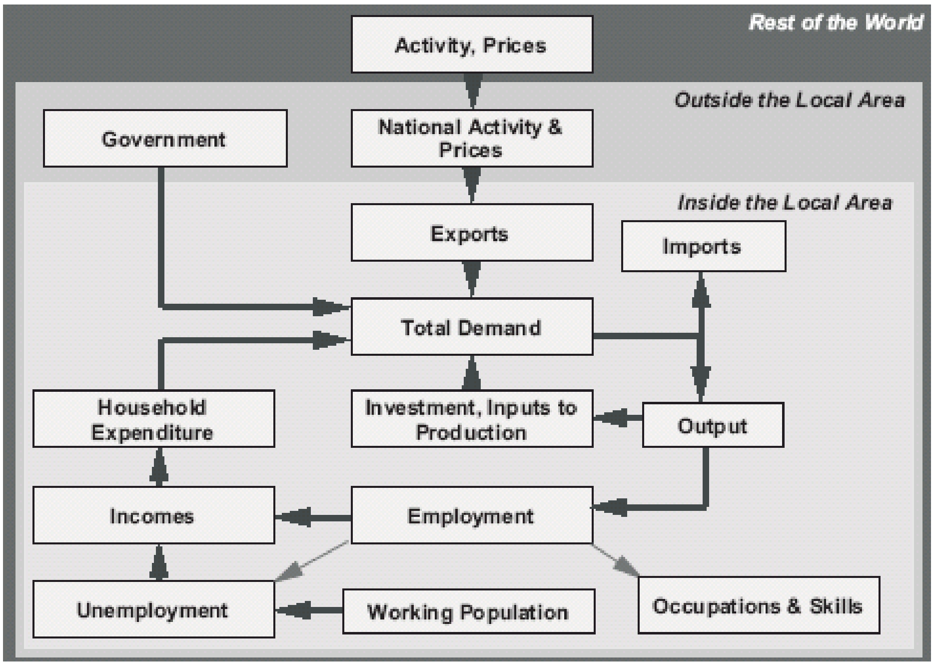

Figure C-1 Structure of the MDM-UK and REEIO models (Cambridge Econometrics, 2003)

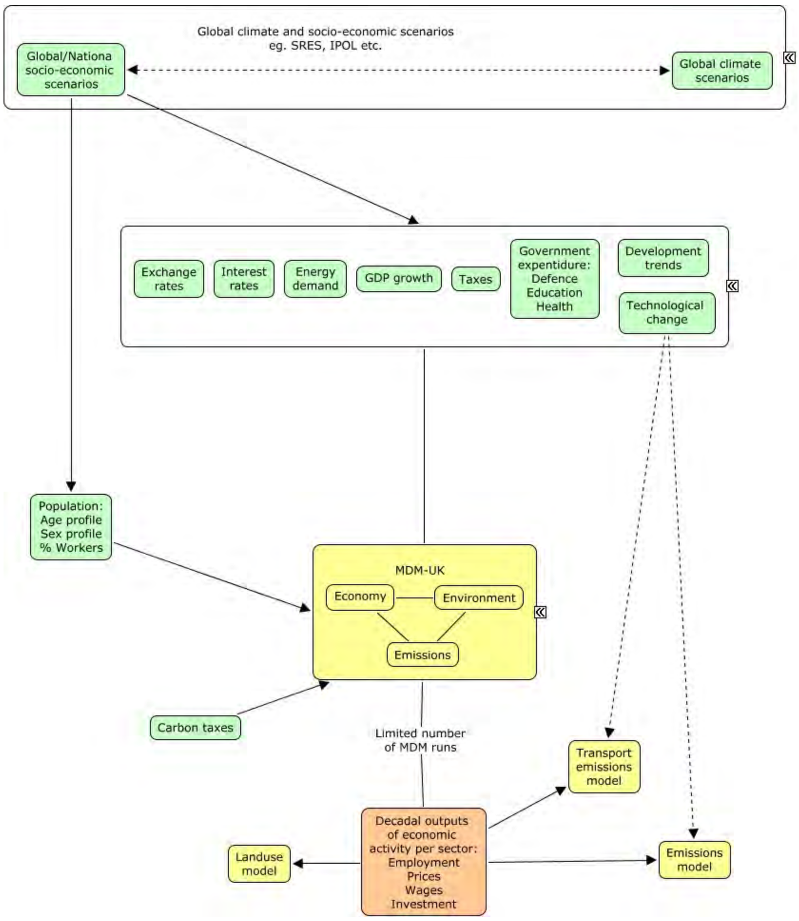

Figure C-2 Overview of the economics model and its interaction with the ULAF

C.3 Similar methodologies

Models for assessing the economics of climate change generally cover a time span of at least 100 years, out to the year 2100. They are generally world models, although there are some country specific models, especially the US and the AIM family for Asia and India. The UK is generally treated implicitly as part of the OECD or the EU.

The Stern report (2006) undertook a survey of models and results (Barker, Qureshi and Köhler, 2006) following Barker, Köhler and Villena (2002). The literature has made a major change to endogenising technical change, such that the results of older models are no longer considered valid. These developments are reviewed in Köhler et al. (2006) and Grubb, Köhler and Anderson (2002).

The best known model is probably the DICE model of Nordhaus (1994).This uses an intertemporal optimising framework to undertake a cost benefit analysis of climate mitigation, treating the world as a single region. Most models in this field are deterministic, but the Sern review undertook analysis using the PAGE stochastic Integrated Assessment Model Plambeck, Hope and Anderson (1997) to provide estimates of the costs of climate change mitigation. This is again a global model, with very limited representation of economics.

There are no equivalent models to MDM or E3MG for the GLA area. The REEIO model developed for the GLA uses MDM economic data as inputs to assess environmental variables. The ENVIROS model does not have a macroeconomic model in it but takes input economics assumptions (also derived from scenarios generated using Cambridge Econometricsmodels) and calculates environmental impacts.

C.4 Input and Output variables

Type	Data	Categories	Resolution	Extent	Timestep	Source
Output (**Y**) variables	Employment	Population per sector	Regional	UK	Annual to 2020, then decadal to 2100	n/a
	Industrial output	GVA per sector	Regional	UK	Annual to 2020, then decadal to 2100	n/a
Initialisation (**X**) variables	Current and historical population demographics	Age; Sex; % Workers	Ward	GLA		Already compiled by CE
	Current and historical exchange rates		UK	Global		Already compiled by CE
	Current and historical interest rates		UK			Already compiled by CE
	Current and historical energy demand		UK			Already compiled by CE
	Current and historical GDP growth		UK			Already compiled by CE

	Current and historical taxation		UK			Already compiled by CE
	Current and historical government expenditure	Defence; Education; Health	UK			Already compiled by CE
Non-urban policy (**S**) variables	Future population demographics	Age; Sex; % Workers	Ward	GLA		SRES
	Future exchange rates		UK	Global		SRES
	Future interest rates		UK			SRES
	Future energy demand		UK			SRES
	Future GDP growth		UK			SRES
	Future national taxation	Fuel tax; Other???	UK			SRES
	Future government expenditure	Defence; Education; Health	UK			SRES
Urban policy (**P**) variables	Future taxation	Fuel tax; Other???	Regional	UK		UIAF stakeholders
Behavioural (**B**) variables	Not applicable for this model					

C.5 Work tasks

- Review available UK socio-economic scenarios (*August 2006-January 2007*)
    - From E3MG outputs
    - From IMCP models (eg. PIK model)
    - From literature
- Review available population growth assumptions (from UN, CPI, SRES, EU, UK and UK socio-economic sources such as the ONS) (*August 2006-January 2007*)
- Implement extension to MDM-UK (*December 2006-March 2007*)
    - Recoding MDM-UK to run (and remain stable) to 2100
    - Provide economic activity outputs in agreed format to landuse module
    - Generate example outputs for testing purposes
- Parameterise MDM-UK for baseline scenario (*April 2007-September 2007*)
    - Define baseline scenario
    - Generate results
- Specification and parameterisation of main economic policy options and specific scenarios of interest, these may include (*April 2007-December 2007*):
    - UK/Global carbon taxes,
    - Effect on London economy of "shocks",
    - Influence of global climate impacts on London economy,
    - Influence of shifts in tourism on London economy *etc.*
- Run further scenarios identified late 2007/early 2008 after further stakeholder consultation (*January 2008-April 2008*)

C.6 References

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Appendix D: Urban land use

D.1 Methodological description

The land use transport model is a cross sectional activity allocation models that accepts exogenous locations and amounts of population and employment suitably broken down to appropriate categories or types and then distributes the endogenous population and employment of the same or different types to small areas of the system. The links between population and employment are simulated as spatial interaction models based on gravity concepts and thus require networks and travel times/costs/distances. The employment and population sectors are tied together using a quasi input outputs structure. The outputs in terms of population and employment are then converted to land uses from which capacities and densities result. The model (Figure D-1 and Figure D-2) would then be interfaced with aggregate control totals of population and employment at the top end and with land use constraints and climate change factors at the bottom or local end.

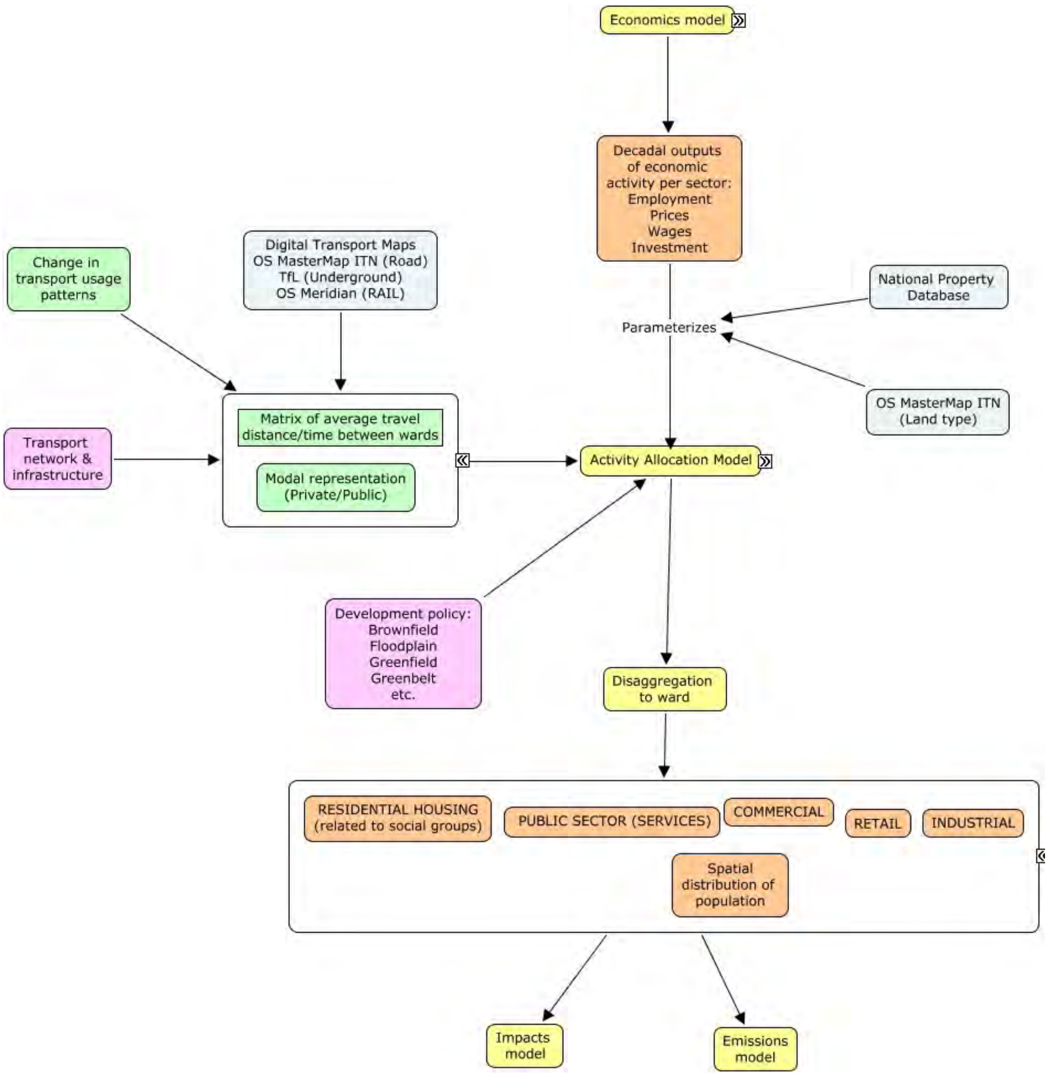

Figure D-1 The landuse model and connections with the ULAF

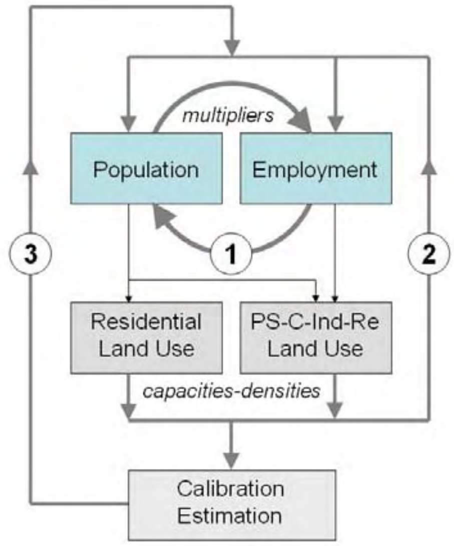

Figure D-2 The landuse activity allocation model

D.2 Similar methodologies

There are a number of substantial reviews of urban landuse models (Oryani and Harris, 1997, Abraham, 1998, Simmonds and Echenique, 1999, Waddell *et al.*, 2001, Benenson and Torrens, 2004). The following summary is only a brief review of the field. Generally, models are considered to be *static*, in that they evaluate the landuse at one moment in time, or *dynamic*, in that they run for a number of time steps, with changes often taking one or more time steps to have an impact on land-use (although some static models can be implemented in a quasi-dynamic mode through successive static simulations). A number of different types of model are now considered here.

Gravity (static) model

Lowry (1964) was the first attempt at formalising the structure of urban systems. The model disaggregated the city spatially, with three activities (industrial and non-local business, retail and local business and households), and an interaction between activities that is governed by the frictional effect of distance. The model runs for only a single timestep, but can be run consecutively to simulate multiple timesteps.

Innovation diffusion (dynamic) model

These models are founded on the work of Hägerstrand (1967), and precursors to the automata and agent-based models discussed later. Rather than consider the situation at a given timestep, these models consider the interactions between timesteps. These interactions occur through local interactions (*eg.* person to person) or from global information (*eg.* media), other interactions may occur from major organisations (Pred, 1975)

System dynamics models

These models are founded in Forrester's (1961) classic text on dynamics, when applied to urban areas (Forrester, 1969). Forrester's ideas are founded in feedback loops and control theory applied to stocks (*eg.* houses, jobs) and flows of information. His models were not spatially explicit, but modelled parameters such as the changing population through time.

Aggregated (dynamical) models

These are conceptual models that capture the aggregate trend of urban behaviour. For example, using ecological predator-prey relationships to model changes in population (*c.f.* Dendrinos and Mulally, 1982, Orishimo, 1987).

Regional (dynamical) models

These models represent a union of the system dynamics and gravity models, where regions are described by stocks (*eg.* population, landuse) and flow between the regions is defined by parameters such as worker location, employment activity, distance to work *etc.*

Cellular Automata (dynamical) models

In CA models, the modelling domain is discretised into cells with each cell having a set of attributes (eg. population, topography, accessibility). The behaviour of the model is governed by global rules and local interactions. Three dimensional CAs have also been developed to attempt to capture high density urban living. Although CA models have produced promising results, methods for their calibration are considered under developed their sensitivity is not yet well understood (Benenson and Torrens, 2004). For example, The MOLAND model is not sufficiently accurate in terms of land use and activity predictions for our purposes (Barredo *et al.*, 2003).

Multi-Agent Systems (dynamical) models

As with the automata models described above, agents are capable of exchanging information between each other, and accepting global rules. However, they extend the automata models by responding to and influencing their environment. Some types of agents will be able to move (*eg.* people) through their environment, whilst others are perhaps more abstract (*eg.* planning organisations). UrbanSim is an example of a MAS model (Waddell, 2002). However, these types of models, whilst providing useful insights, require information at a resolution that is unavailable and are also more computationally demanding.

Proposed approach

The MEPLAN model (Echenique *et al.*, 1990) that is often used by the Department for Transport in London and the Southeast (and used in the EU PROPOLIS and EPSRC SOLUTIONS projects) is (as we currently understand its implementation) too coarse for the purposes of this project, and is also consultancy software and so can not be embedded within the UIAF.

The approach proposed for the UIAF is as result of a pragmatic compromise between the availability and resolution of data, and the resolution needed for impacts analysis. A gravity model approach is proposed with relatively small zones of analysis, but with significantly more sophisticated consideration of the transport network and socio-economic classes than those used in earlier applications. These models have proven themselves sufficiently robust over the previous fifty years of development to provide credible results, are not computationally expensive and can maximise use of the available data without extrapolating beyond the data's accuracy and resolution.

D.3 Variables

Type	**Data**	**Categories**	**Resolution**	**Extent**	**Timestep**	**Source**
Software output	Quasi-dynamic (decadal) fully GIS interfaced London population/employment interaction and land use model for 2010-2100					
Output (**Y**) variables	Residential land use change		Ward and/or $1x1km^2$	GLA & TG	Decadal 2010-2100	
	Non-residential land use change		Ward and/or $1x1km^2$	GLA & TG	Decadal 2010-2100	
	Disaggregated population change		Ward and/or $1x1km^2$	GLA & TG	Decadal 2010-2100	
	Employment activity change		Ward and/or $1x1km^2$	GLA & TG	Decadal 2010-2100	
Initialisation (**X**) variables	Current and historical digital map data	MasterMap; Road, Rail and Underground network; 1971, 1981, 1991, 2001 census	Ward	GLA & TG		OS, TfL; ONS
	Residential and non-residential land	LiDAR; MasterMap	Ward	GLA & TG		OS; ONS.
	Population	Social group from 1971, 1981, 1991, 2001 census	Ward	GLA & TG		ONS
	Current and historical employment	Economic super-sector	Ward	GLA; TG and other UK regions		Economics model

	Journey to work		Ward	GLA; TG and other UK regions		WICKED (SIDS)
	Journey to shop		Ward	GLA; TG and other UK regions		WICKED (SIDS)
Non-urban policy (**S**) variables	Future employment	Population per sector	Regional	UK	Annual to 2020, then decadal to 2100	Economics module
	Future industrial output	GVA per sector	Regional	UK	Annual to 2020, then decadal to 2100	Economic module
Urban policy (**P**) variables	Development constraints	Brownfield; Greenbelt; Urban green-space; Flood risk zones	Ward	GLA & TG	Annual to 2020, then decadal to 2100	NLUD; Multimap; LandCoverMap 2000; Flood risk module
	Changes to journey to work	Modal type	Ward	GLA & TG	Annual to 2020, then decadal to 2100	Transport futures
	Changes to journey to shops	Public; Private; Travel time between ward	Ward	GLA & TG	Annual to 2020, then decadal to 2100	Transport futures
Behavioural (**B**) variables	Not applicable for this module					

D.4 Stakeholder input

1. Input may be needed from organisations involved in the Thames Gateway development in relation to generating population and employment scenarios for the flooding impact analysis module (*i.e.* specifically within the Thames Gateway zone). This input will be needed once we have developed the Stage 1 model (Expected: October/November).
2. GLA Economics will provide a range of key information for the spatial modelling package. Primary data-sets for the spatial modelling package should be acquired in August/September. This data includes GLA wide (ward-level) population, employment, transport infrastructure (digital map form).

D.5 Work tasks

AF – Alistair Ford; SE – Stephen Evans; MB – Mike Batty; SB – Stuart Barr

Note: tasks, assignments and completion dates have been derived on the basis of 6 months of SE time @ 2-days per-week = 15months from 1st Aug to end October 2007. 18 months of AF time @ 5-days per-week = 18months from 1st June to end December 2007.

1. Agree economic/employment sectors/categories with economic modelling work package. This needs to take into account GLA Economics categories.
   Staff: AF to lead + liaise with JK + MB to lease with GLA Economics in the first instance.
   Importance: Essential. V.High priority.
   Complete: End August 2006.

2. Agree social/demographic population subdivision groups to employ in land use simulation.
   Staff: AF to lead discussion + SB, MB & SE.
   Importance: Essential. V.High priority.
   Complete: End August 2006.

3. Formally agree and define transport modal groups to employ in land use simulation.
   Staff: AF to lead discussion + SB, MB & SE.
   Importance: Essential. V.High priority.
   Complete: End August 2006.

4. Agree the geography (relevant spatial extent) of GLA + Thames Gateway ensuring appropriate for economic modelling and flooding mitigation

Staff: AF to lead discussion + SB, MB & SE in cooperation with economic modelling and flood mitigation groups.
Importance: Essential. V.High priority.
Complete: End August 2006.

5. Formally agree and define non-GLA+Thames Gateway zones of influence (e.g., to account for commuting).
Staff: AF to lead discussion + SB, MB & SE.
Importance: Essential. V.High priority.
Complete: End August 2006.

6. Acquire primary census ward level data from CASWEB/UK Boarders for 2001 base year. Includes ward boundaries, population (by agreed social groups) etc. Data to be structured as a standard joined map layer & as a vector for simulation model.
Staff: AF.
Importance: Essential. High priority.
Complete: End August 2006.

7. Acquire primary census ward level travel to work statistics for 2001 base year categorised as agreed. Data to be structured as a standard joined map layer & as suitable tabulated format for simulation model.
Staff: AF
Importance: Essential. High priority.
Complete: Mid September 2006.

8. Acquire primary ward level GLA Economics travel to work date for 2001 base year categorised as required. Data to be structured as a standard joined map layer & as suitable tabulated format for simulation model.
Staff: SE + lease with AF
Importance: Essential. High priority.
Complete: Mid September 2006.

9. Agree base flood mitigation scenario requirements re: data, constraints, economics, land use information and scale.
Staff: AF to lead with SB+MB+SE + Economic modelling + Flood mitigation.

Importance: Essential. High priority.

Complete: Mid September 2006.

10. Generate a primary modal transport network for GLA+Thames Gateway + zones of influence. Data to be structured as standard geometric networks in the first instance.

    Staff: AF+SB

    Importance: Essential. V.High priority.

    Complete: End September 2006.

11. Generate JS metrics from modal network models at the level of ward interaction. Metrics to be structured as matrices for simulation modelling.

    Staff: SB+AF.

    Importance: Essential. V.High priority.

    Complete: End October 2006.

12. Generate Boolean constraint layers for flood mitigation base scenario.

    Staff: AF.

    Importance: Essential. High priority.

    Complete: End October 2006.

13. Develop stage 1 simulation model of population and employment for 2100. Translate to physical residential and non-domestic land requirements per-2001 ward. Initial testing on synthetic data set.

    Staff: MB + SE.

    Importance: Essential. V.High priority.

    Complete: End October 2006.

14. Develop fully integrated GIS version of the stage 1 simulation model.

    Staff: SE.

    Importance: Desirable/Essential. High priority.

    Complete: End December 2006.

15. Apply stage 1 model to GLA data for flood mitigation scenario. Evaluate model output and undertake key refinement as required.

    Staff: MB + SE

Importance: Essential. V.High priority.
Complete: End November 2007.

16. Apply stage 1 model to GLA+Thames Gateway data for flood mitigation scenario. Evaluate model output and undertake key refinement as required.
    Staff: MB + SE
    Importance: Essential. High priority.
    Complete: End December 2007.

17. Develop and implement a spatial assignment module to map residential and non-domestic land requirements at the ward level for 2100.
    Staff: AF
    Importance: Essential. High priority.
    Complete: End December 2007.

18. Provide scenario 1 physical land requirement 2100 map for flood mitigation work.
    Staff: AF+SB+MB+SE
    Importance: Essential. V.High priority.
    Complete: End December 2007.

19. Evaluate stage 1 model by simulating 1981 to 2001 land use requirements and compare to current data-sets for a sample of GLA wards.
    Staff: AF+SB+MB+SE
    Importance: Desirable. Medium priority.
    Complete: End January 2007.

20. Review, agree and implement alternative flood management scenarios as required for stage 1 implemented model.
    Staff: AF+SB+MB+SE + economic modelling + flood impacts.
    Importance: Desirable. High priority.
    Complete: End February 2007.

21. Agree key base-line scenarios for stage 1 model for other climate impacts work packages.
    Staff: AF+SB+MB+SE + economic modelling + climate impacts and emissions accounting modules.

Importance: Essential. High priority.

Complete: End January 2007.

22. Implement key base-line scenarios for stage 1 model for climate impacts and emissions accounting modules.
    Staff: AF+SB+MB+SE
    Importance: Essential. High priority.
    Complete: End March 2007.

23. Design and agree work allocation of stage 2 quasi-dynamic model and feedbacks to be implemented.
    Staff: AF+SB+MB+SE
    Importance: Desirable. Medium priority.
    Complete: End February 2007.

24. Implement stage 2 quasi dynamic model. Including fully GIS interfaced.
    Staff: AF+SB+MB+SE
    Importance: Desirable. Medium priority.
    Complete: End May 2007.

25. Agree with mitigation desirable stage 2 quasi-dynamic scenarios to evaluate and agree allocation of work tasks across mitigation scenarios.
    Staff: AF+SB+MB+SE + all mitigation groups.
    Importance: Desirable. Medium priority.
    Complete: End May 2007.

26. Run stage 2 quasi-dynamic model simulations for mitigation groups.
    Staff: AF+SB+MB+SE.
    Importance: Desirable. Medium priority.
    Complete: End August 2007.

27. Produce best practise case studies of software and simulation results for stakeholder presentation and demonstration.
    Staff: AF+SB+MB+SE.
    Importance: Essential. High priority.

Complete: End October 2007.

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Appendix E: Transport emissions

E.1 Methodological description

Figure E-1 is a flow chart giving an idea of the proposed methodological process for the transport accounting tool. It will not be possible within the resource available to examine micro-level adaptations at a very local level aimed at changing behaviour on the ground. However this is an important area for future work.

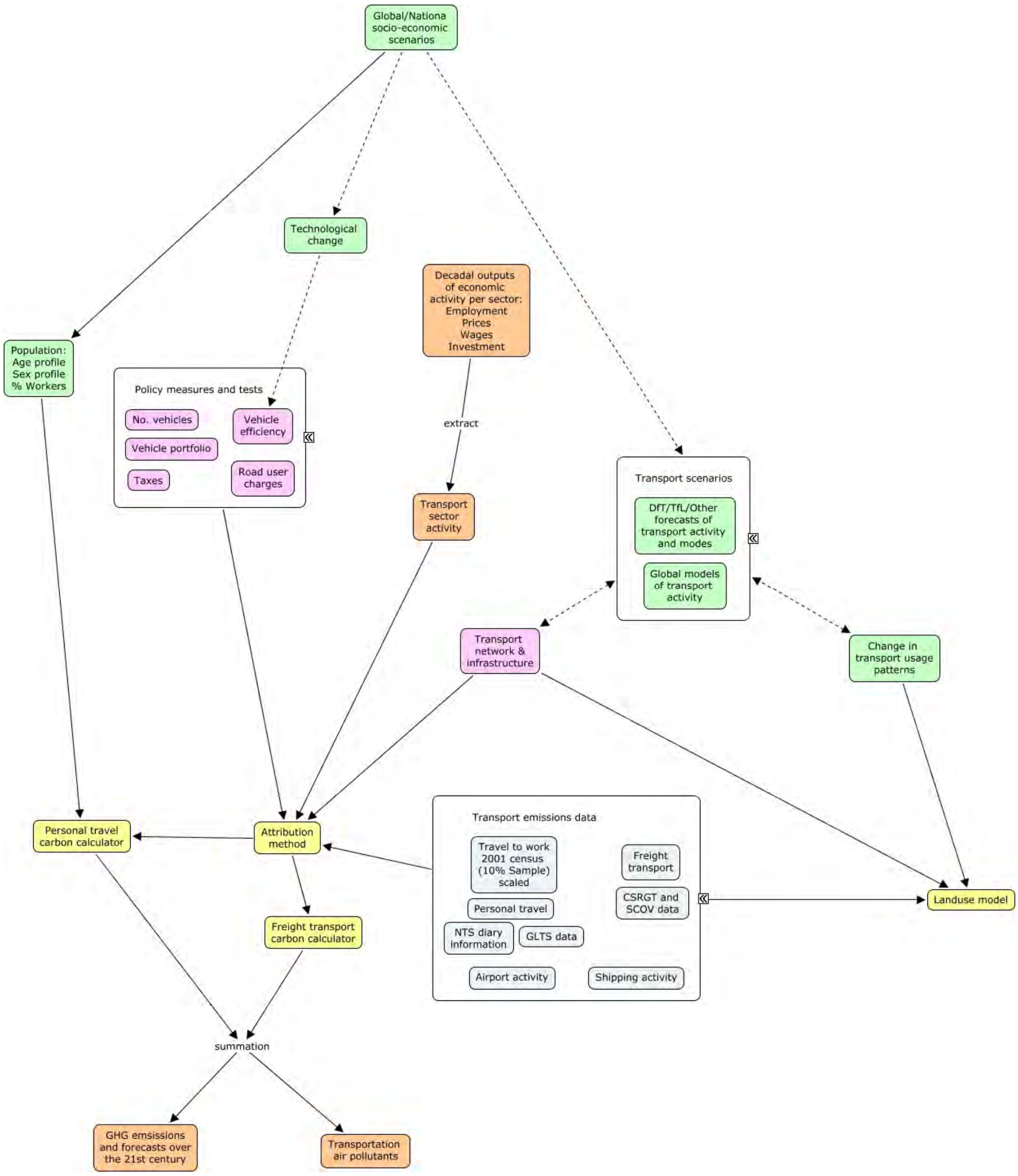

Figure E-1 The methodological process for the transport accounting tool.

E.2 Review of similar methodologies.

A review of relevant literatures is being undertaken as part of the initial task of the project. This will include a review of work which has looked at

- boundary issues when dealing with discrete geographical areas such as London; and
- allocation issues relating to the combination of freight and personal transport emissions.

This includes the work by AEA for DEFRA (Goodwin *et al*., 2005a) on regional emissions and for the DTI on the regional allocation of emissions from the road sector (Goodwin *et al*., 2005b); work by the ONS for EUROSTAT (Francis, 2004) on household emissions by region; the REWARD study reports on the allocation of emissions between RDAs (REWARD, undated) and also the Environmental Accounts produced by ONS (ONS, 2005). This is a critical element of the study not just in identifying data sources but more importantly in exploring the assumptions by which emissions are attributed to the household unit.

Our initial assumption is that we will attempt to allocate all transport emissions to households. This is relatively straightforward in the context of personal trips given the National Travel Survey data. This approach would provide consistency between regions and avoid the risk of double counting trips that pass through more than one region. Even so for a city like London which attracts a large number of travel to work, shopping and leisure trips from outside the region the issue of allocation is complex even if related to households. We need to know the proportion of passenger transport kilometres within London made by individuals from households located outside London in order to allocate the correct amount to Londoners. We can also use the NTS data on passenger transport trips made by Londoners.

The allocation of emissions from business travel and freight and distribution is more contentious. It is relatively easy to identify the emissions from large fixed point sources such as factories, power stations etc. Yet ideally these emissions should be allocated to the consuming regions which would increase the share of emissions allocated to London. However, it is of equal interest in policy terms to identify the contribution of different types of producer and service provider. Similar issues arise relating to travel by overseas visitors in London and by Londoners overseas and when allocating transport emissions from imports and exports.

It is clear that whatever approach we adopt needs to be both clearly and logically justified and where possible consistent with other activities in the Cities Research Theme.

E.3 Stakeholder input

We envisage a need for stakeholder input, predominantly from the GLA and Transport for London, at a number of key points in the project:

- When considering the range of transport policy scenarios that could influence emissions for London;
- At the stage of assessing the outputs in terms of their comparability with other estimates and in terms of assessing their perceived accuracy. This would be required both at the initial results stage at the end of 2006 and later in terms of the future look.

E.4 Variables

Type	Data	Categories	Resolution	Extent	Timestep	Source
Software output	A spreadsheet that implements the transport emissions accounting calculation					
Output (**Y**) variables	Transport GHG and air pollutant emissions (CO_2; CO; Pb; NO_2; O_3; PM; SO_2 *etc.*)	Land (personal by modal type and freight); Water; Air based transportation	Ward	GLA	Decadal to 2050	
Initialisation (**X**) variables	National Transport Survey	Individual trip records		UK		
	London Area Transport Survey	Individual trip records		GLA		
	Continuing Survey of Road Goods Transport	Individual trip records				
	Survey of Company Owned Vans	Individual trip records				
	UK fleet composition	Individual trip records				
	Airport activity	Take off and landing records	Airport	GLA		
	Shipping activity	Berthing and trip records	GLA	GLA		
Non-urban policy (**S**) variables	DfT National Road Forecasts	Road type; Area type; Time of day; Vehicle		UK	1997-2031	

		(road traffic) type.				
	Tyndall Transport Futures: World Transport scenarios project			Global	1995; 2025; 2050	
	TfL Transport Futures			UK		
Urban policy (**P**) variables	Number of vehicles			GLA		
	Type of vehicles			GLA		
	Vehicle efficiency			GLA		
	Fuel (or other 'green') taxes			GLA (& UK?)		
	Road user charging			GLA (& UK?)		
	Transport infrastructure network and capacity			GLA		
Behavioural (**B**) variables	Influence of policy on behaviour change			GLA		Surveys

E.5 Work tasks

The key worktasks are as follows:

1. Review and select/devise emissions allocation methodology of Carbon from transport to the population of London (January 2007)
2. Review and select/devise methodology for attribution of trans-GLA-boundary Carbon emissions (January 2007).
3. Updating and further development of Carbon calculation software (January 2007):
    a. Adaptation of existing transport Carbon calculation software to handle travel diary data from national travel surveys
    b. Calculate emissions of Carbon from personal transport use for London
4. Development of a method to calculate freight transport emissions of Carbon and allocation of those emissions to London (April 2007).
5. Combination of results from (3) and (4) to produce overall emissions figures for London (February 2007).
6. Prediction of future emissions levels according to a range of transport policy scenarios (December 2007).

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Appendix F: Non-transport emissions

F.1 Methodological description

An emissions accounting tool has been coupled with a scenario analysis tool to enable users to explore the impact of different assumptions about energy demand, technology change and energy generation etc. CO_2 emissions can be counted from: Energy, Industrial processes, Waste emissions, Population and sewage works and Agriculture. GRIP currently only considers energy in the scenario analysis. Other further additions include non-CO_2 GHG (*eg.* NO_x and CH_4) and heat emissions accounting components. This module will also allow stakeholders to study the emissions profile between 2010-2050 in order to explore the cumulative emissions reductions necessary in order to achieve a given emissions reduction target.

The module will work in an iterative way, with the impacts of the stakeholders inputs made on both the demand and the supply sides being represented in real time in terms of their effect on emissions. These “decisions” made by the stakeholder pertain to the quantity and type of energy consumed within each sector, and with respect to the supply side the mechanism and type of energy used in the generation of secondary fuels.

There are a variety of flows that will need to take place so that overall end user energy consumption can be tracked, together with the associated primary energy. In addition with the appropriate economic data, the level of energy intensity, energy efficiency and carbon efficiency changes associated with the stakeholders visions. Overall there are in excess of 200 variables that are either manipulated directly or that result from stakeholder inputs.

The emissions will be reported spatially. Whilst point source emissions can be reported exactly, others may have to be disaggregated according to land use and/or some other measures of activity.

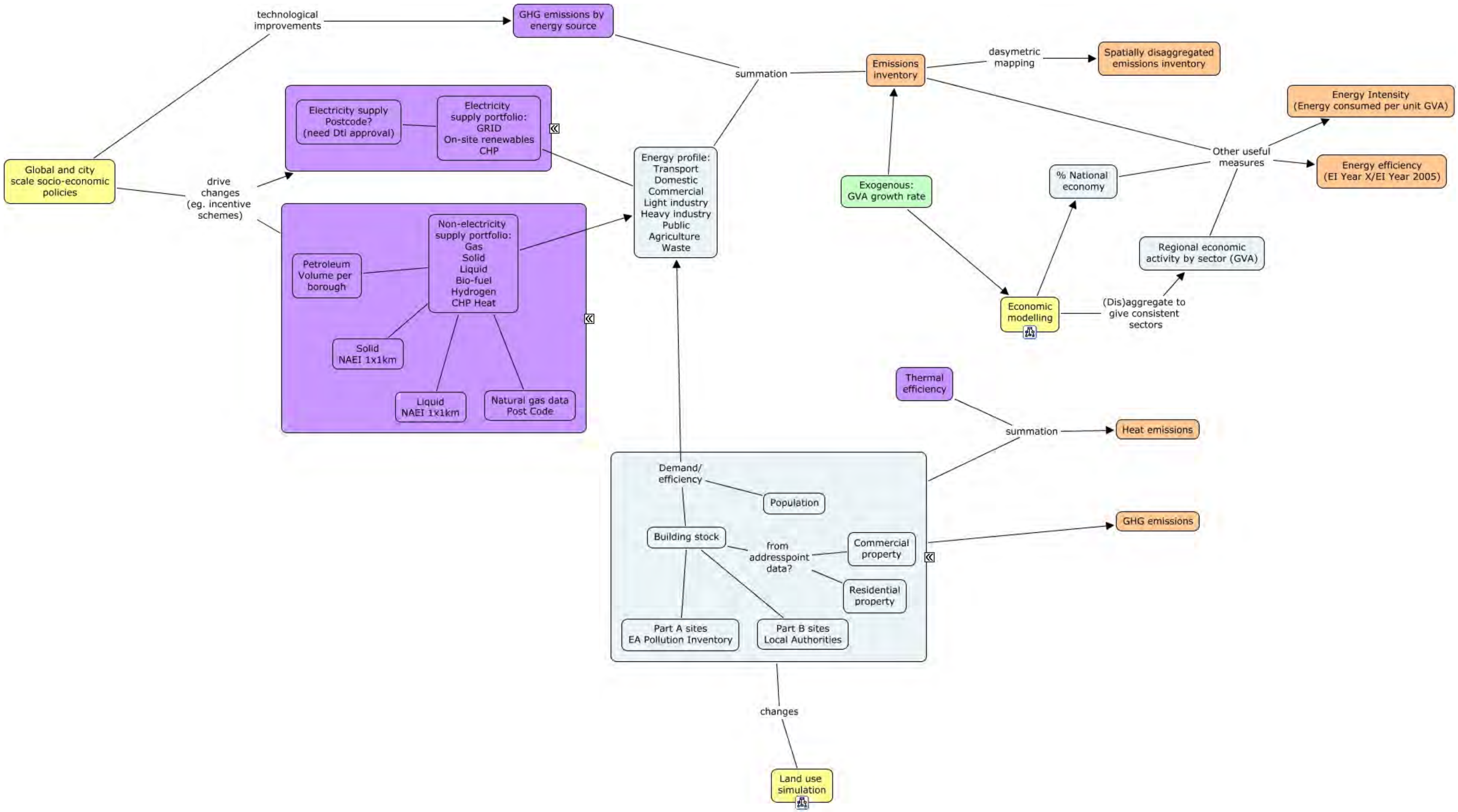

Figure 6-1 Summary of data movement in GRIP calculation

F.2 Review of similar methodologies

The methodology for estimating emissions in the first instance will be based upon the GRIP methods, these are based upon the methods suggested by the IPCC which are the ones utilised in the formation of the national inventory. The GRIP method for forming an inventory allows for all areas of emissions to be quantified and spans the six main greenhouse gases. The scenario module as described above needs the inputted data to be formatted in a particular way for it to be included and utilised. The lack of completeness of ICLEI (not all emission sources) and differences in the format are the two reasons why we are not using the ICLEI approach. The GRIP scenario approach is also non-deterministic, in that it is down to the stakeholder to decide what the energy future looks like rather than a model that determines how it is meant to look under certain (*eg.* economic) conditions. This makes the tool unique, it is there to provide the quantitative element to a qualitative discussion to help guide discussion in emissions scenario formation appropriately.

Further statement required on relationship with LAEI and downscaling methodology.

F.3 Variables

Type	Data	Categories	Resolution	Extent	Timestep	Source
Software output	A spreadsheet that implements the basic emissions inventory calculation A spatially explicit interface formatted for London (although easily transferred to other UK regions and cities) that allows the testing of city-scale mitigation strategies and reports the outputs spatially to activity at the ward scale.					
Output (**Y**) variables	Quantity of energy consumed	Emissions sector				
	Energy type	Emissions sector	Ward	GLA	Decadal to 2050	
	Greenhouse gas emissions	NO_x; CH_4; CO_2 *etc.*	Ward	GLA	Decadal to 2050	
	Heat emissions	Emissions sector	Ward	GLA	Decadal to 2050	
	Local air pollutants	CO; Pb; NO_2; O_3; PM; SO_2 ???? by Emissions sector	Ward	GLA	Decadal to 2050	
Initialisation (**X**) variables	DTi energy inventory			GLA		DTi
	EA Pollution Inventory			GLA		EA
	Combined Heat and Power (CHP) usage			GLA		LCCA?
	On-site renewables database			GLA		LCCA?
Non-urban policy (**S**)	Population			GLA		Landuse module

variables	UK/international tax and incentives			GLA		
Urban policy (**P**) variables	London tax and incentives			GLA		
	Efficiency	Generation; Transmission		GLA		
	Building stock			GLA		Landuse module
	Electricity supply portfolio	By supply type		GLA		
	Non-electricity supply portfolio	By supply type		GLA		
	Emissions reduction technology			GLA		Consistency check with global scenarios
Behavioural (**B**) variables	Effectiveness of incentives at changing behaviour			GLA		

F.3.1 Emissions sectors

Current emissions sectors:

- Domestic
- Services
    - Public
    - Administrative
    - Commercial
- Heavy Industry
- Light Industry
- Energy Industry
    - Fugitive Emissions
- Transport
    - Road
    - Rail
    - Air (Heathrow and City)
    - Sea (eg port of London)

F.3.2 Energy supply types

Energy supply types:

- Hydrogen Production Technique & Energy Source
- GRID provision, UK and London
    - By Production Technique & Energy Source
- CHP provision and energy source
- On-Site Renewables Type

F.4 Work tasks

- Complete inventory for London 2000-2005 (October 2006)
- Emissions calculator spreadsheet (December 2006)
- Develop spatially explicit stakeholder emissions scenario tool (August 2007)
- Develop emissions scenarios consistent with socio-economic scenarios (August 2007)
- Produce emissions component of Urban Integrated Assessment Framework (December 2007)
- Stakeholder Interviews (February and June 2008)
- Analysis & Write – up (July 2008)

Appendix G: Flood risk impacts module

G.1 Methodological description

The aim of this impact assessment module is to investigate the flood risk in the tidal Thames Estuary (approximately between Kingston upon Thames and Southend). This module draws on extensive experience of broad scale flood risk analysis in the project team (Hall *et al.*, 2003, Dawson *et al.*, 2005, Dawson and Hall, 2006) and will seek to work closely with the ongoing Thames Estuary 2100 initiative which is developing a Flood Risk Management Plan for London and the Thames Estuary for the next 100 years. The module couples a stochastic model of storm surge and flow with a structural reliability analysis of flood defences, flood inundation simulations and damage estimation.

The influence of changing precipitation and sea level can be explored. Risk management policy options that do not require additional hydrodynamic simulations, such as landuse changes, can be readily explored. However, only a limited number of adaptation options that seek to reduce flood risk through altering the hydrodynamic behaviour of the Thames Estuary can be tested. These include construction of new flood barriers, flood storage devices, managed retreat and channel modification. Where they generate significant emissions, infrastructure construction projects, and the operation of online barriers (this may become more frequent with increased sea level rise) can be input into the emissions accounting module.

G.2 Variables

Type	Data	Categories	Resolution	Extent	Timestep	Source
Software used	EA Weather Generator (EARWIG) model developed at Newcastle University					
Output (**Y**) variables	Floor risk profiles	People; Property; Environment *etc.*	Ward (or 1x1km)	GLA & TG	Decadal to 2100	
Initialisation (**X**) variables	Defence properties	Soil; Crest level; Geometry; Construction material; Location		GLA & TG		EA's National Flood and Coastal Defence Database
	Topography		5m	GLA & TG		LiDAR; NextMap IFSAR
	Depth-damage functions			GLA & TG		Multi-Coloured Manual
	Channel properties	Bathymetry; width; location		GLA & TG		
	River flow records			At Kingston		
	Storm surge records			At Southend		
	Impacts	People; Property; Environmentally sensitive areas *etc.*		GLA & TG		Landuse model
Non-urban policy (**S**) variables	Sea level rise			At Southend		UKCIP
	Changes to storm surge characteristics			At Southend		UKCIP and more recent work by Met Office

	Precipitation change			1x1km		UKCIP downscaled using Earwig
Urban policy (**P**) variables	Embankment crest level raising					
	Channel modification					
	Upstream reservoirs and flow control devices					
	Dike rings and bunds					
	Flood proofing and stilts					
	Floodplain characteristic	Urban fabric; Landuse; Infrastructure location and properties				
	Estuary barriers					
	Managed retreat					
Behavioural (**B**) variables	Not applicable to this module					

G.3 Work tasks

- Scoping Thames Estuary flood management issues (January 2007)
- Design and implement flood risk impacts module (March 2007)
- Perform preliminary demonstration exploring the impact of land use change on flood risk over the 21st century (April 2007)
- Integrate flood impacts model into UIAF (May 2007)
- Analysis and reporting (August 2007)

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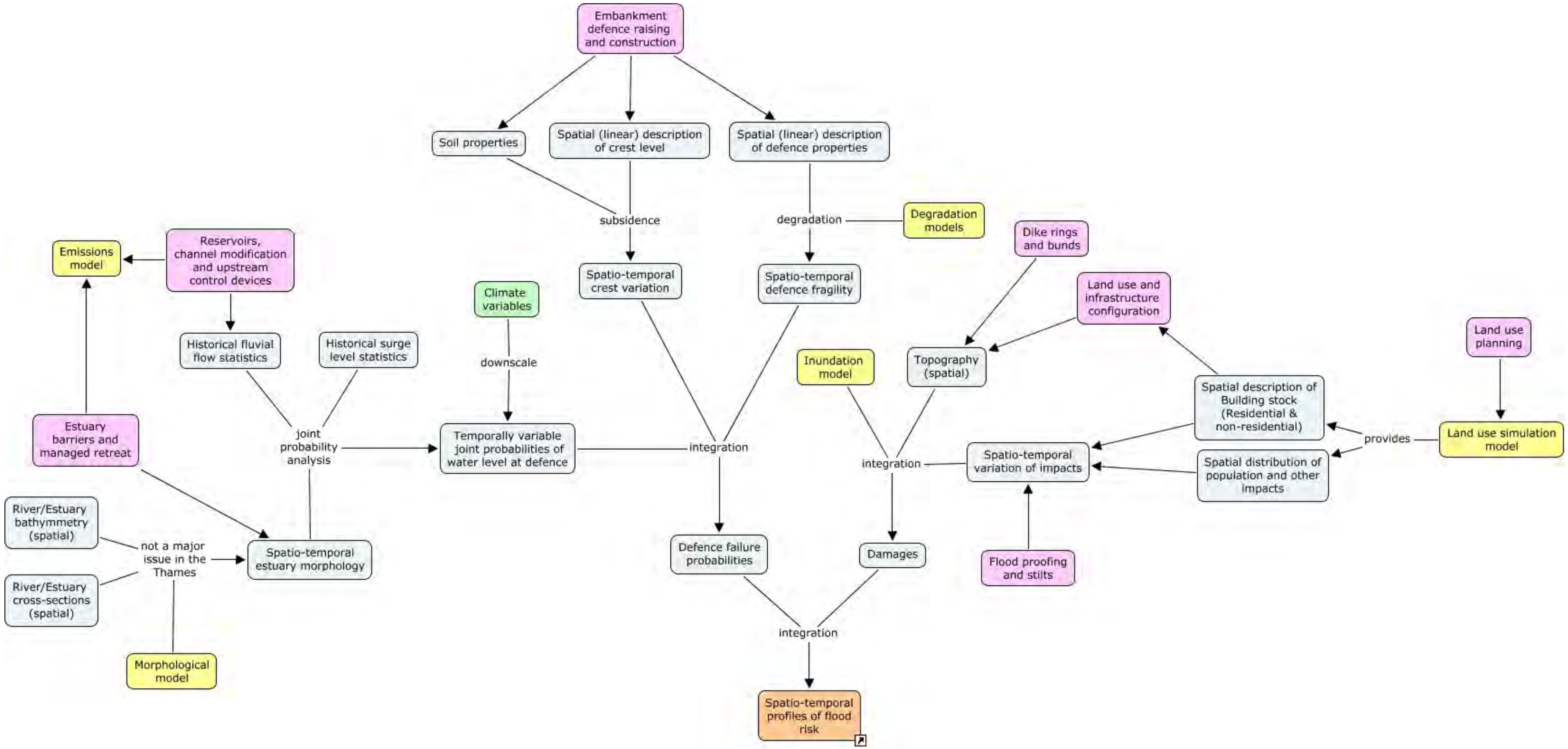

Figure G-1 Overview of the flood risk impacts module and its interaction with the ULAF

Appendix H: Water resources impacts module

The aim of this impact assessment module is to investigate the water resource in the Thames Region i.e. the Thames catchment to Kingston upon Thames (TQ177698), which has a catchment area of 9948 km^2. In the first instance the area will be assessed using the Environment Agency's conceptual rainfall runoff model: CATCHMOD. Subsequently, it is hoped that Thames Water will be involved with testing of new management strategies and scenarios for future operations using their existing water resource model: WARMS.

H.1 Methodological description

Figure 1 shows the proposed methodology.

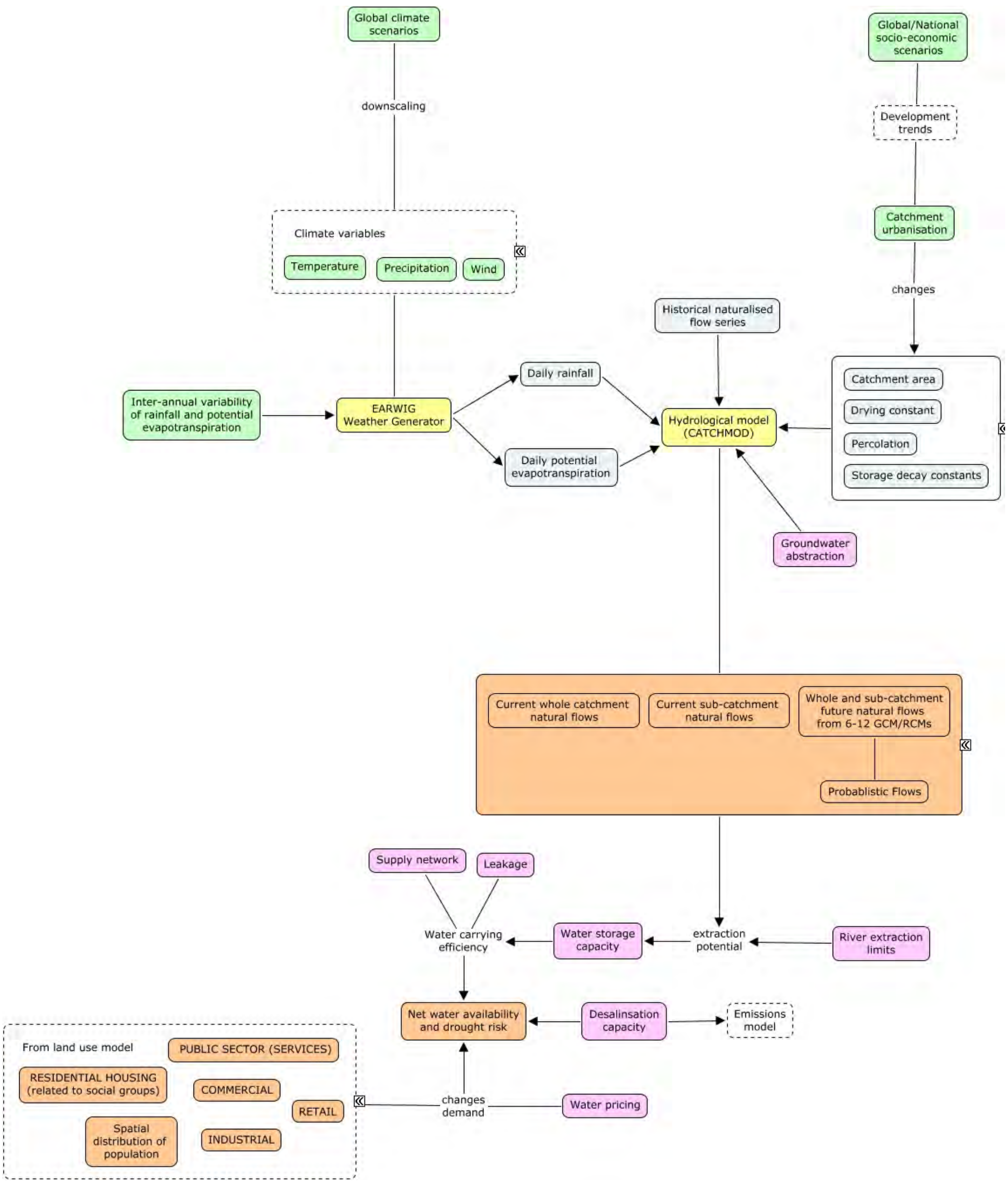

Figure H-1 Proposed water resources impact assessment methodology

The methodology can effectively be divided into 3 sections. The first deals with any input that is required to drive the CATCHMOD model. The second section describes CATCHMOD in more detail in terms of how it is set-up and the main output. The final section investigates other external factors that need to be considered in a water resource study.

H.2 Environment Agency Rainfall and Weather Impacts Generator: EARWIG

EARWIG was developed as Newcastle University in collaboration with Climatic Research Unit, University of East Anglia (Kilsby *et al.*, 2006). The software consists of two stochastic models: the first produces rainfall series at a daily resolution, subsequently the second model derives meteorological variables required to calculate potential evapotranspiration based on rainfall. Scenarios can be generated for the control period (1961-1990) based on observed data, as well as for the UK Climate Impact Programme (UKCIP02) scenarios for three time slices (2020's, 2050's and 2080's). Future scenarios are generated by fitting the models to observations which have been perturbed by application of change factors derived from UKCIP02 mean projected changes in each variable.

EARWIG will be developed to allow the PRUDENCE (Christensen *et al.*, 2002) climate scenario change parameterisation to drive the future scenarios for 2020's, 2050's and 2080's, based on the A2 scenario. The PRUDENCE output to be used consists of six GCM/RCM combinations, Table 1 shows such combinations.

Table 1. PRUDENCE scenarios

RCM	GCM
HIRHAM	HadAM3H A2
HIRHAM	ECHAM4/OPYCA2
HadRM3P	HadAM3P
RCAO	HadAM3H A2
RCAO	ECHAM4/OPYCA2
Arpège	Observed SST

At present EARWIG predicts less variation in rainfall and PET than is currently being observed. Therefore sequences will be modified to account for historical and future scenarios of inter-annual variability.

H.3 CATCHMOD

CATCHMOD is a rainfall runoff model which produces river flow simulations from rainfall and potential evaporation time series inputs. The model structure allows the model to be run on up to ten hydrologically similar zones (based on geology, topography or land use). These zones are then summed to give total flow. The zones are calibrated individually therefore allowing water to pass through the stores at different appropriate rates. Each hydrological zone has 5 physically-based parameters:

- Catchment area
- Drying constant
- Direct (bypass) percolation
- Upper store decay constant
- Lower store decay constant

It is suggested that the obvious approach is to model representative catchments as well as Thames at Kingston. Davis (2001) did this for the following catchments which have a good geographic and hydrological spread, and for which there are working models:

- River Lee at Feildes Weir: 1036 km^2(Chalk)
- River Mole at Kinnersley Manor: 142 km^2 (Clay, Urban)
- River Colne at Bibury: 106.7 km^2 (Oolites, Cotswolds)
- River Lambourn at Shaw: 234.1 km^2 (Chalk)

These catchments are shown in Figure H-2.

Outputs for the model will include current flows for four sub-catchments to represent the different geology and land use across the catchment which will contribute to estimating current flows for whole Thames catchment to Kingston. Future flows for the whole catchment and four sub-catchments will be generated using six different GCM/RCM combinations (PRUDENCE output). Subsequently a Bayesian approach (Tebaldi et al. 2005) will be applied to combine these into a single probabilistic output by effectively suggesting a likelihood factor to the range of output data. Similar output will also be produced for changed land use and water management policy.

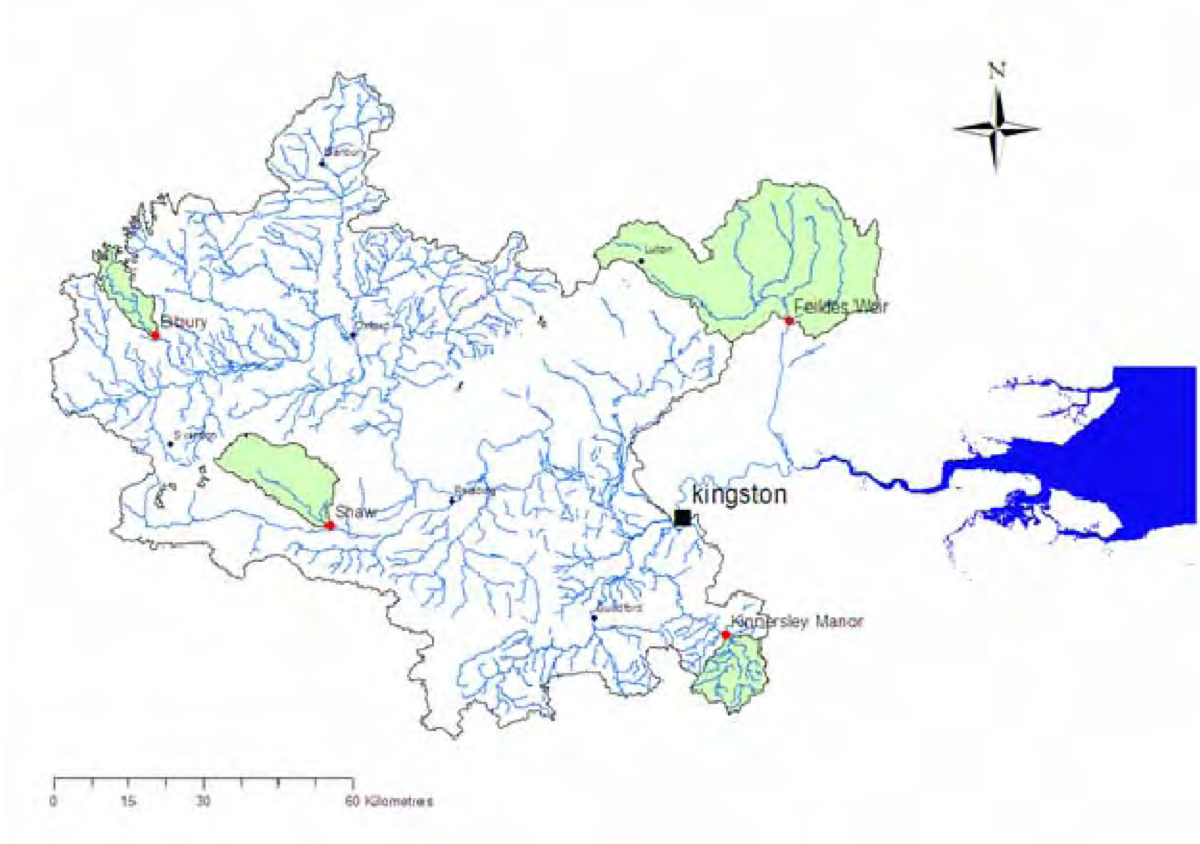

Figure H-2 Map of Thames catchment showing significant watercourses

H.4 External factors affecting water resources

Based on the flows generated as CATCHMOD output, it is proposed that we derive what we term as 'flow adjustment based on external factors'. In this section the main drivers in affecting the resource are defined as: management policy options, land use change and demand change simulation. Management policy options could include improvements to existing supply infrastructure such as water pipe replacement schemes or the proposed reservoir at Abingdon. Although the land use model being developed for the project only covers the GLA, whereas CATCHMOD will be established for the catchment to Kingston, outside of this boundary, it may be possible to estimate changes in urban form in surrounding major towns e.g. Oxford or Reading. Such changes may affect the resource reaching the catchment outlet. Demand change simulation would include aspects such as change in population, industry growth and changes in building stock, as well as leakage reduction and water pricing, the latter would require input from Thames Water.

H.5 Review of similar methodologies

In assessing water resources, water companies incorporate climate change by applying Arnell's (2002) calculated flow factors, based on UKCIP02 scenarios to identify the resource zones that are sensitive to climate change (Environment Agency, 2003). Arnell's method is essentially a 'perturbation method' concerned only with changes in mean climate by altering the observed input data to a hydrological model on a monthly, seasonal or annual basis according to GCM projections. However, this method only allows examination of mean flows, without consideration of variability and extremes, both of which will have the most effect on hydrological processes, in particular when considered in a water resources context. EARWIG uses PDRY (proportion of dry days in a month) as an input which will generate future scenarios with different PDRY series, whereas Arnell's approach uses the same sequence as historical data. Arnell's factors are only based on one climate scenario UKCIP02, whereas our approach using six combinations of GCMs/RCMs will allow a probabilistic output.

Wilby and Harris (2006) used CATCHMOD to examine the response of the entire Thames catchment to future climate provided by an ensemble of four GCM's, two emissions scenarios, and two downscaling methods. Information about the modelling skill of specific GCM/downscaling technique pairs in reproducing summer effective rainfall was used to weight the different outputs. PDF's of low flows were produced, conditional upon this weighting, and on the assumption of no weighting, and the results were stratified to identify the relative contribution to uncertainty of each component. Tebaldi *et al.* (2005) applied a Bayesian technique to the output of an ensemble of AOGCM's to predict regional temperature change for the same experiment previously undertaken by Giorgi and Mearns (2002), using the same weighting criteria, that is using both model skill and model agreement, but allowing for correlation between current and future climates. The advantage of the Bayesian approach is to provide a more detailed assessment of the model performance.

H.6 Stakeholder Input

The main stakeholders with a direct interest in such a study are:

- Thames Water;
- The Environment Agency; and
- The GLA.

Advice on setting-up and running CATCHMOD has been sought from the Environment Agency. Thames Water have been invited to participate with the testing of new management strategies and scenarios for future operations using their existing water resource model: WARMS. The GLA have an interest in the outputs of the study and its implications for their residents and businesses and in understanding the effectiveness of any instruments at their disposal (including water pricing).

H.7 Variables

Type	Data	Categories	Resolution	Extent	Timestep	Source
Software used	Thames catchment parameterised version of the EA's CATCHMOD hydrological/water resources model EA Weather Generator (EARWIG) model developed at Newcastle University					
Output (**Y**) variables	Inter-annual variability of historic rainfall					
	Inter-annual variability of potential evapo-transpiration (PET)					
	Future daily rainfall and PET output from	Six GCM/RCM combinations				
	Future naturalised flows	Six different GCM/RCM combinations; Catchment land use change scenarios	Sub-catchments	Thames catchment		
Initialisation (**X**) variables	GCM/RCM outputs	Six-Twelve different GCM/RCM combinations (from PRUDENCE project) of rainfall	GCM/RCM grid			PRUDENCE project
	Current and historical flow rates at Kingston (Teddington weir)		Sub-catchments	Thames catchment		
	Current and historical		Sub-catchments	Thames		

	naturalised flows			catchment		
	Historical evidence for inter-annual variability of rainfall and PET		Sub-catchments	Thames catchment		
	EARWIG outputs	Rainfall and PET	5x5km	Thames catchment		
	Soil and land-use parameters	Catchment area; Drying constant; Direct (bypass) percolation; Upper store decay constant; Lower store decay constant	Sub-catchments	Thames catchment		
Non-urban policy (**S**) variables	Population change		Thames catchment	Thames catchment		
	Up-catchment demand change		Thames catchment	Thames catchment		
	Inter-annual variability		Sub-catchments	Thames catchment		
	Catchment land use		Sub-catchments	Thames catchment		
Urban policy (**P**) variables	Storage capacity		Sub-catchments	Thames catchment		
	Desalinisation capacity		Thames catchment	Thames catchment		

	Leakage rate		Thames catchment	Thames catchment		
	Water demand	Per capita; Industry	Sub-catchments	Thames catchment		
	Water pricing	Domestic; Industry	Thames catchment	Thames catchment		
Behavioural (**B**) variables	Effectiveness of incentives at reducing demand		Thames catchment	Thames catchment		

H.8 Work tasks

The timing of delivery for the work tasks is dependent on when CATCHMOD is made available to us, although we would expect all tasks to be completed by February 2007, with the first two tasks (inter-annual variability and PRUDENCE scenarios into EARWIG).

- Deriving inter-annual variability of historic rainfall and PET (October 2006)
- Integrating the six GCM/RCM scenarios into EARWIG (November 2006)
- CATCHMOD simulations of (December 2006):
    - Current naturalised flows for the four sub-catchments
    - Current naturalised flows for the whole Thames catchment to Kingston
    - Future naturalised flows for the four sub-catchments
    - Future naturalised flows for the whole Thames catchment to Kingston
- Bayesian approach to producing a single probabilistic future flow series (February 2007)
- Adjustment of the flow output based on external factors (February 2007)

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Appendix I: Heat impacts module

I.1 Methodological description

The heat impacts model will have two tiers of analysis described in the following two sections, a high level analysis that looks at urban scale impacts only, and an intermediate level that considers urban morphological design and the implications of building and land use changes. The detailed level, not considered here would consider individual buildings.

'Re-engineering' cities to reduce the impact of the urban heat island may seem to be an unrealistic and overwhelming challenge, however, it is relevant over the extended timescales considered in this research programme. It is worth recalling that building lifespans are typically 40-50yrs, although commercial buildings are often designed to have lifespans up to 100 years and road lifespans are approximately 30yrs (although this can be extended by temporary resurfacing). All this means that by the end of the 21st century London will have had a very high percentage of its roofs and paving surfaces replaced – or nearing replacement age – and many of its (non-protected) buildings too. A short term, intensive, heat island mitigation programme is likely to be too costly to implement even if there was the political and public will to implement it but it is meaningful and feasible to think about heat mitigation through strategically re-engineering cities over long timespans to mitigate!!!!

I.1.1 High level analysis

This level of analysis involves the correlation of heat emissions with temperature variables that have been downscaled to the urban area. This will be intersected with information on population vulnerability to enable the impacts of heat on health to be explored under scenarios of socio-economic and climate change to be explored.

However, this level of analysis will not enable the interaction between urban form and buildings on the intensity of the urban head island to be explored.

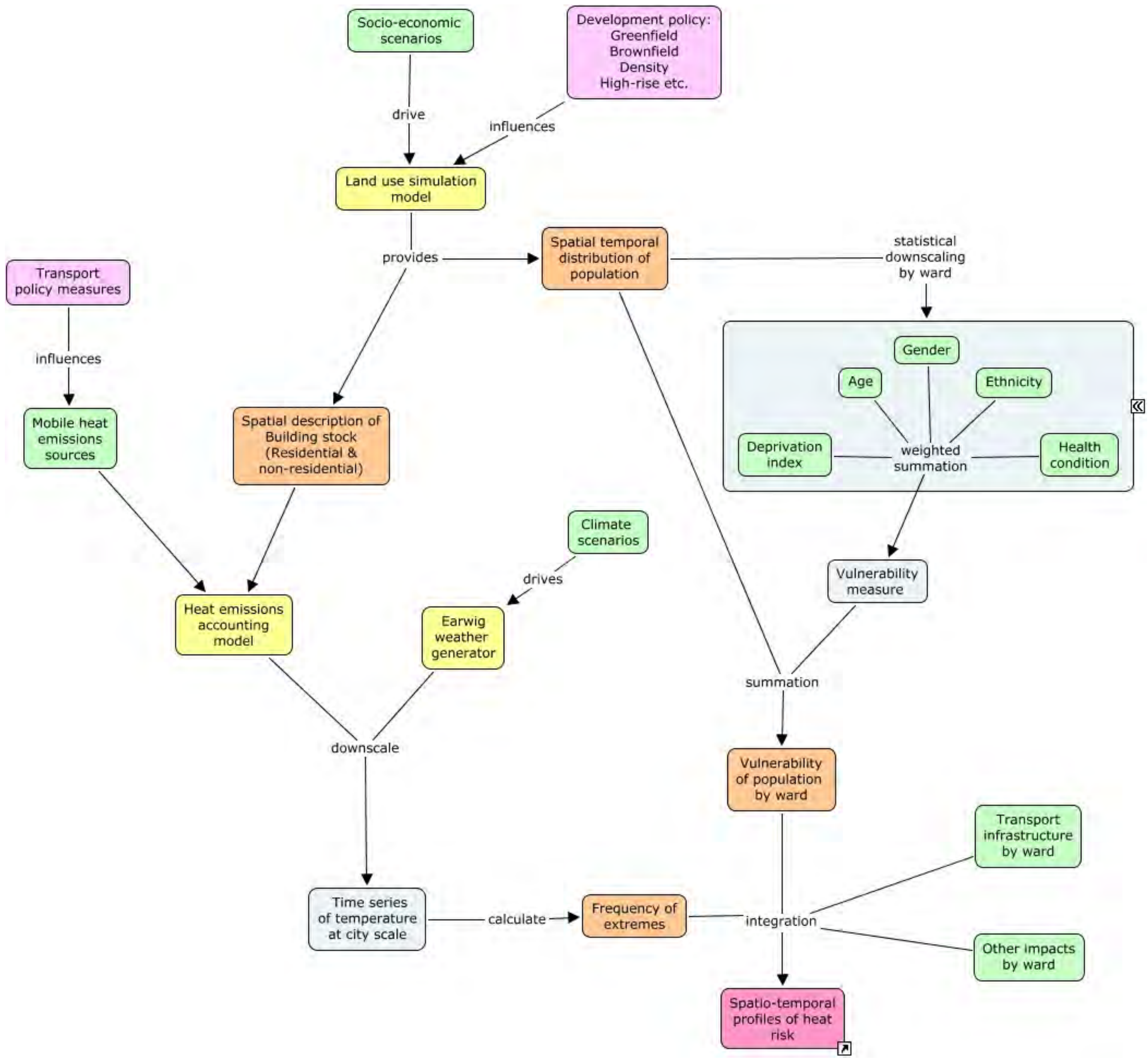

Figure 6-2 Overview of the high level heat risk impacts module

I.1.2 Intermediate level analysis

Many of the adaptation options associated with the policy variables outlined in Section I.3 will not be testable using the above methodology. The ability to implement this level of analysis relies on interaction with the SCORCHIO project. The advantages of this method are that the interaction between climate variables and urban form can be analysed – therefore real engineering solutions can be tested.

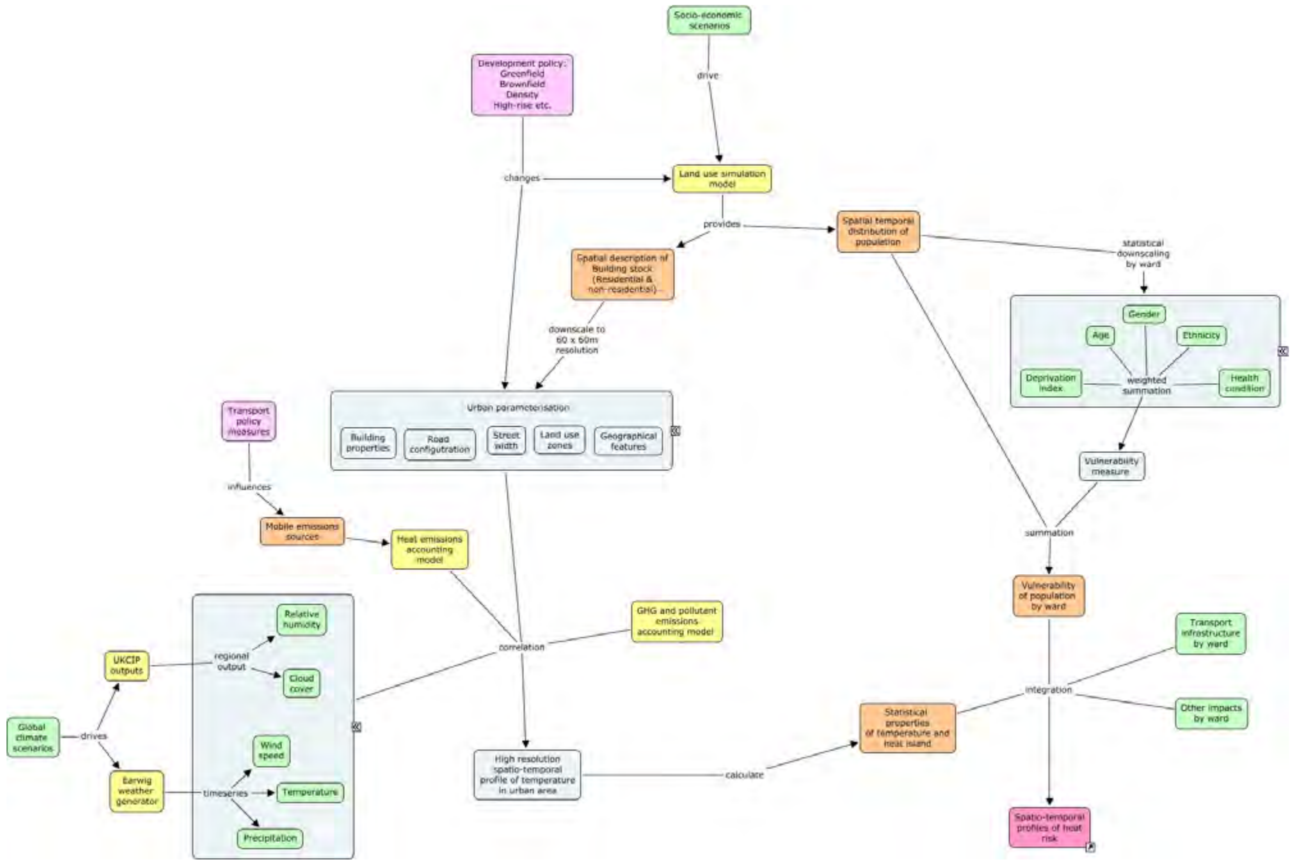

Figure 6-3 Overview of the intermediate level heat risk impacts module

I.2 Review of similar methodologies.

Methods used to model the urban heat island are based on either generating regression and correlation coefficients for key variables or employing numerical simulation techniques. High level methods are used to estimate maximum heat island intensity based on relationships between one or more variables.

Remote sensing has been employed in many of these models to parameterise them (*eg.* Weng, 2001). Parameterisations are either based on city-scale averages of parameters such as population density (*eg.* Chen *et al.*, 2005) or on spatially variable parameters based on land cover that can include normalised difference vegetation index (NDVI), mean building height, building density *etc.*.

The methodology proposed here will not use numerical simulation methods, but will build on existing correlation methods to establish relationships between temperature and urban properties to include information on urban and street morphology.

The vulnerability index will be constructed after a literature review, but is expected to be based upon the index used by the GLA (2006).

I.3 Variables

Type	Data	Categories	Resolution	Extent	Timestep	Source
Output (**Y**) variables	Urban Heat Island	Air temperature; Surface temperature; Actual temperature; Temperature relative to rural reference;				
	Heat based landuse classification index	Building; Landuse				
	Heat vulnerability index	Population				
Initialisation (**X**) variables (Vulnerability function)	Demographics	Age; Gender; Deprivation; Ethnicity	Ward	GLA		ONS Census; DEFRA's IMD
	Health condition	*eg*. Heart, respiratory disease, diabetes, fluid and electrolyte disorders and some neurological disorders	Ward	GLA		ONS Census
	Transport infrastructure accessibility		Ward	GLA		ONS Census
Initialisation (**X**)	Downscaled	Timeseries ; Average ;	50x50km		Decadal to 2100	UKCIP

variables (Climate variables)	temperature from GCM/RCM	Seasonal variability				
	Remotely sensed temperature data		60x60m		Decadal to 2100	Landsat ETM+
	Weather station temperature data		Stations across London		Hourly	
	Wind speed		50x50km		Decadal to 2100	UKCIP
	Cloud cover		50x50km		Decadal to 2100	UKCIP
	Relative humidity		50x50km		Decadal to 2100	UKCIP
	Precipitation	Percentage change; Interannual variability	50x50km		Decadal to 2100	UKCIP
	Air pollution	Concentration of GHGs; Photochemicals; Other pollutants that create local greenhouse effect			Decadal to 2100	APRIL
Initialisation (**X**) variables (Urban parameterisation)	Building and infrastructure properties	Location; Construction materials; façade/roof material; design material; orientation; albedo	Individual buildings	GLA		Addresspoint; Mastermap
	Heat emissions		Point sources; Mobile sources; Area sources	GLA		
	Urban form	Building orientation;		GLA		

		building proximity; building heights; street configuration; street width; vegetation and water				
	Geographical features	Topography; Watercourses; Surround region		GLA		
	Landuse	Configuration of residential; commercial; industrial; vegetation; water zones		GLA		NLUD; Addresspoint; Mastermap; LandCoverMap 2000
Non-urban policy (**S**) variables	Population change		Ward	GLA	Decadal to 2100	Landuse model
Urban policy (**P**) variables	Building stock change	Building density; Geometric properties and design; Building cooling design		GLA	Decadal to 2100	Landuse model
	Urban morphology change	Street spacing; Building orientation;		GLA	Decadal to 2100	
	Construction materials	High-albedo paving and building materials; Vegetation and water		GLA	Decadal to 2100	

		features; Rain capture devices;				
	Air pollution			GLA	Decadal to 2100	APRIL
Behavioural (**B**) variables	Not applicable to this module					

I.4 Work tasks

1. Downscaling of urban weather variables
    a. High level: Temperature
    b. Intermediate: Temperature; wind; precipitation *etc*.
    c. Under scenarios of climate change
2. Aggregate information on spatial variation of temperature in urban areas
3. Classification of buildings, urban landuse and geography
4. Correlation of urban temperature and urban form
5. Downscaling between Land use model and additional information required in heat module inputs
6. Vulnerability index
    a. Full literature review
    b. Design vulnerability index
7. Evaluation of risks
    a. Heat and personal health
    b. Other impact damage functions: *eg*. transport infrastructure

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Appendix J: Full Urban Integrated Assessment Framework

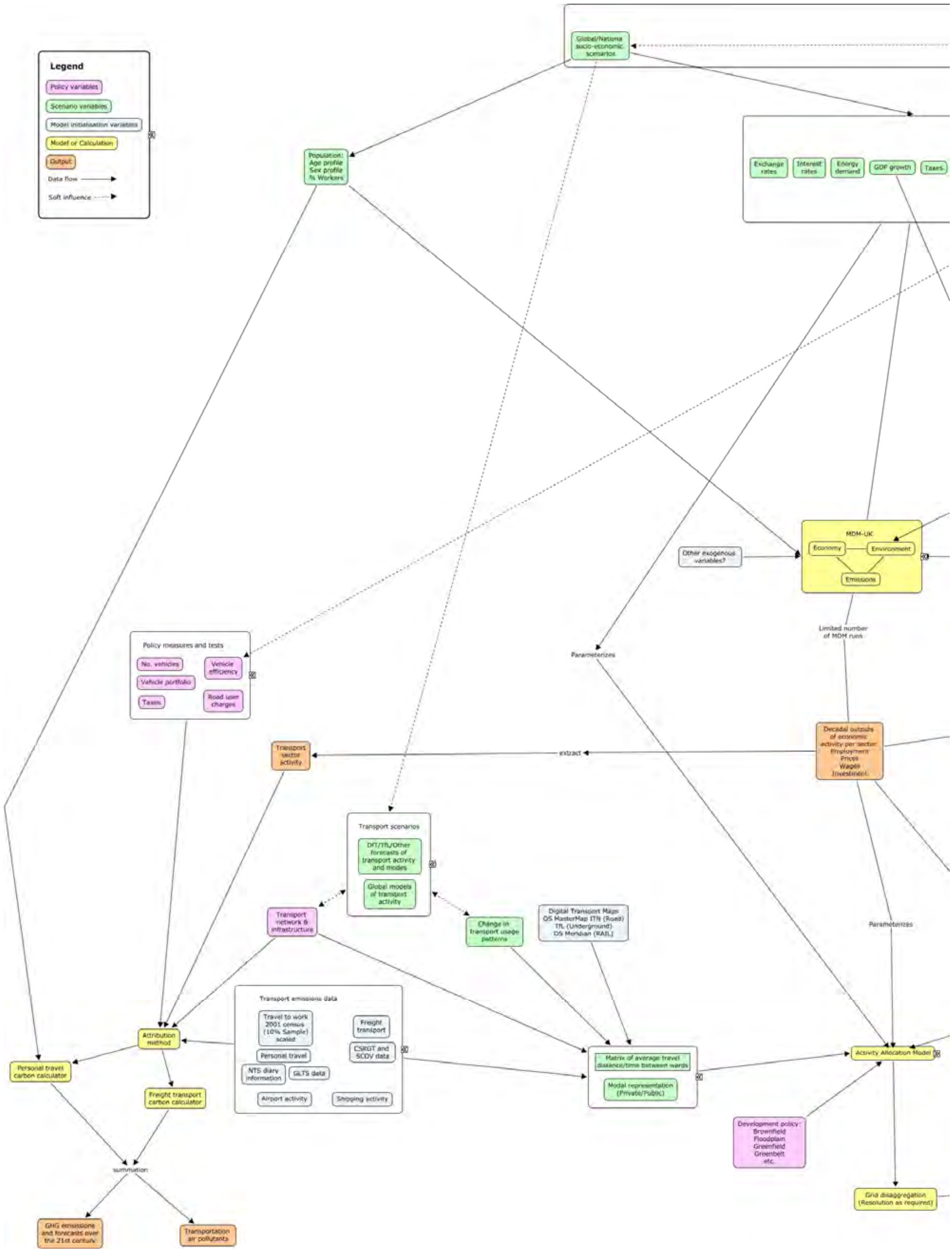


Figure J-1 (Part I) Detailed overview of the linkages in the IUAF (only shows one, water resources, impacts module)

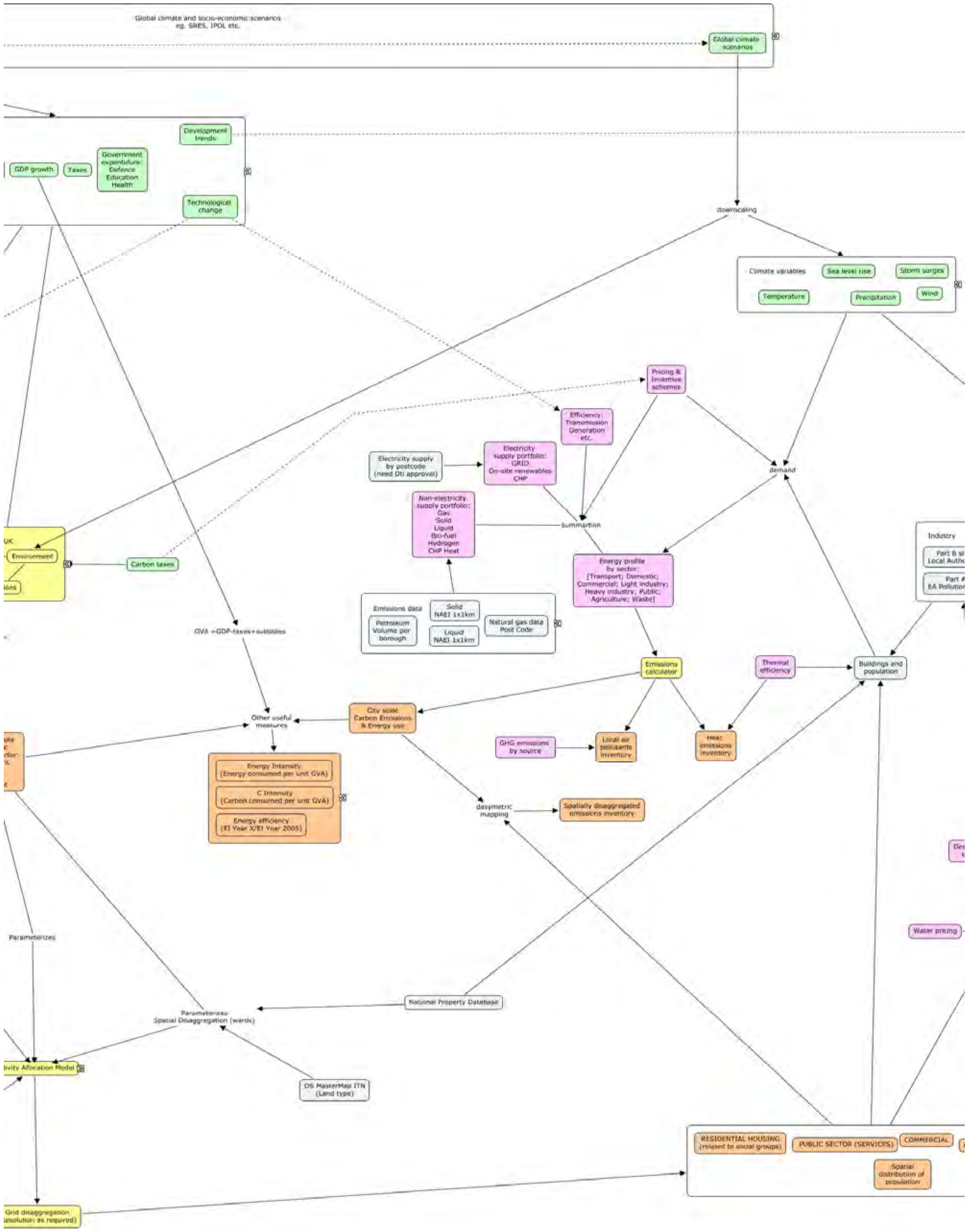


Figure J-1 (Part II) Detailed overview of the linkages in the IUAF (only shows one, water resources, impacts module)

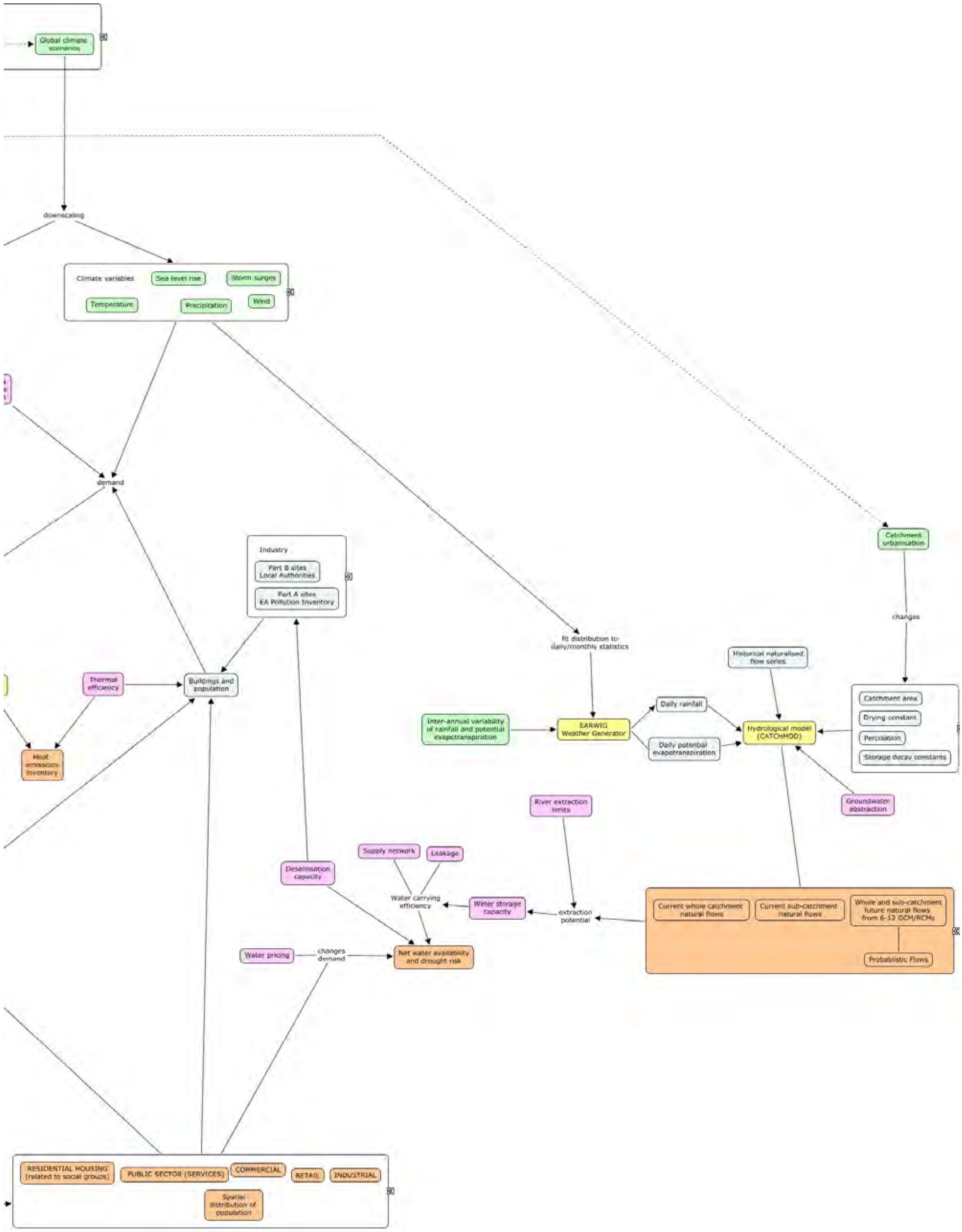
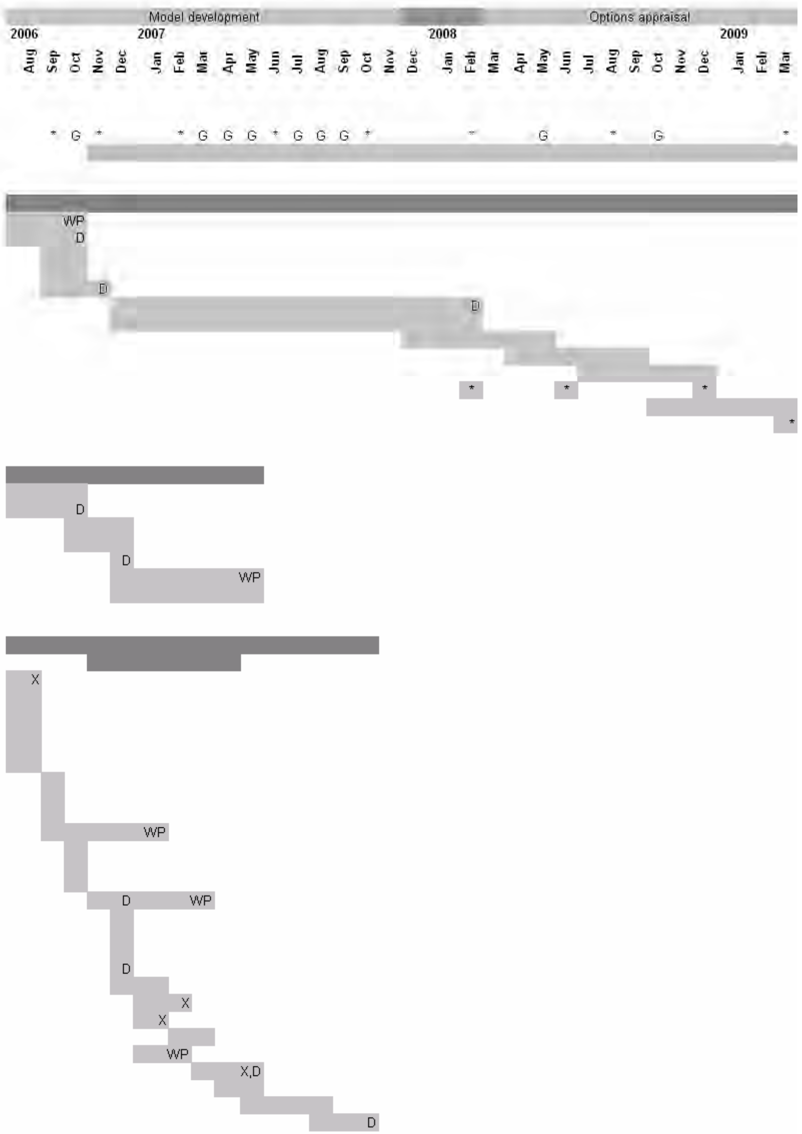


Figure J-1 (Part III) Detailed overview of the linkages in the IUAF (only shows one, water resources, impacts module)

Appendix K: Detailed workplan

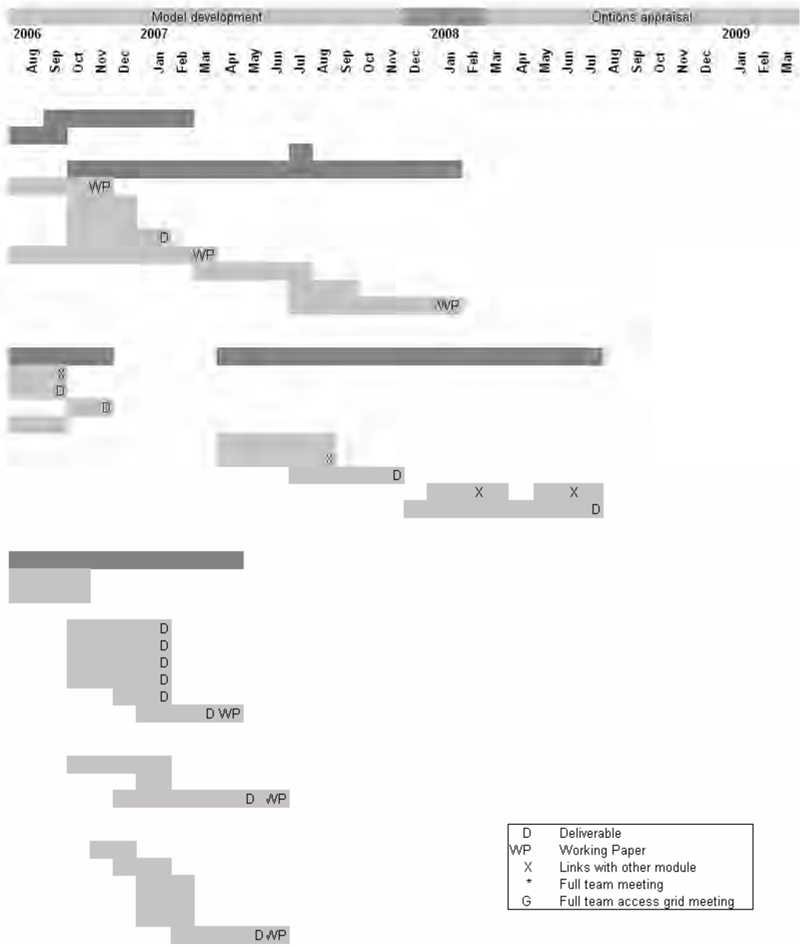
Tyndall°Centre for Climate Change Research — Cities Theme Work Plan

Tyndall Ref Codes	Ref No.	Module	Worktask	Lead staff	Linkages
6.1	1	**Management**		**JH**	
	1.1		Project management		
	1.2		Team meetings (Bilateral meetings not shown)		
	1.3		Project website	RD	
6.1	2	**Integrated Assessment**		**RD**	
				RD	
	2.1		Scoping report	RD	
	2.2		Implementation report	RD	
	2.3		Agree global/national scenarios	RD	All
	2.4		Agree London specific scenarios	RD	All
	2.5		Specification of IA interface	RD	
	2.6		Integration of models	RD	
	2.7		Development of tool and interface	RD	
	2.8		Development of options portfolios	RD	All & Stakeholders
	2.9		Policy testing	RD	
	2.10		Uncertainty and robustness testing	RD	
	2.11		Stakeholder workshop	JH	All & Stakeholders
	2.12		Final Cities theme report	RD	
	2.13		Stakeholder launch event	JH	All & Stakeholders
6.2	3	**Economics**		**JK**	
			Contract	JK	
	3.1		Establish output data format	JK	Landuse, Emis, (Trans?)
	3.2		Run MDM baseline	JK	
	3.3		Develop and implement scaling method	JK	
	3.4		Parameterise policy scenarios	JK	
	3.5		Run policy scenarios and disseminate data	JK	Landuse, Emis, Trans
	3.6		Iterate scenarios and user interface development	JK	
	3.7		Review and possible extension of MDM to 2100 timescale	JK	Landuse, Emis, Trans
6.2	4	**Landuse**		**SB**	
			Contract	AF	
			Contract	SE	
	4.1		Establish input format (economic/employment sectors/categories)	AF	Econ, Emis
	4.2		Establish social/demographic population subdivisions	AF	
	4.3		Define transport modal groups	AF	Trans?
	4.4		Agree the geography (relevant spatial extent) of GLA + Thames Gateway	AF	
	4.5		Formally agree and define non-GLA+Thames Gateway zones of influence	AF	
	4.6		Acquire primary census ward level data (population, boundaries etc.)	AF	
	4.7		Acquire primary census ward level travel to work statistics for 2001	AF	
	4.8		Acquire primary ward level GLA Economics travel to work data for 2001	SE	
	4.9		Agree base flood risk assessment scenario requirements	AF	Flood
	4.10		Generate a primary modal transport network	AF, SB	
	4.11		Generate JS metrics from modal network models at the level of ward	SB, AF	
	4.12		Generate Boolean constraint layers for flood risk assessment base scenario	AF	Flood
	4.13		Develop stage 1 simulation model of population and employment	MB, SE	
	4.14		Develop fully integrated GIS version of the stage 1 simulation model	SE	
	4.15		Apply stage 1 model to GLA data for flood risk assessment scenario	MB, SE	Flood
	4.16		Apply stage 1 model to GLA+Thames Gateway data for flood risk assessment	MB, SE	Flood
	4.17		Develop and implement spatial assignment module	AF	
	4.18		Provide 2100 map for flood impacts module	AF, SB, MB, SE	Flood
	4.19		Evaluate stage 1 model by simulating 1981 to 2001	AF, SB, MB, SE	
	4.20		Review, agree and implement alternative flood risk assessment scenarios	AF, SB, MB, SE	Flood
	4.21		Agree key base-line scenarios for stage 1 model	AF, SB, MB, SE	All impacts & emissions
	4.22		Implement key base-line scenarios for stage 1 model for other impacts	AF, SB, MB, SE	All impacts & emissions
	4.23		Design and agree work allocation of stage 2 quasi-dynamic model	AF, SB, MB, SE	
	4.24		Implement stage 2 quasi dynamic model and GIS interface	AF, SB, MB, SE	All impacts & emissions
	4.25		Agree stage 2 quasi-dynamic scenarios	AF, SB, MB, SE	
	4.26		Run stage 2 quasi-dynamic model simulations	AF, SB, MB, SE	
	4.27		Produce best practise case studies of software and simulation results		



Tyndall°Centre for Climate Change Research — **Cities Theme Work Plan**

Tyndall Ref Codes	Ref No.	Module	Worktask	Lead staff	Linkages
6.3	**5**	**Transport**		**MT**	
				HW	
				SM	
				PT	
				Unappointed	
	5.1		Review transport emissions allocation methods	MT, AB	
	5.2		Implement emissions attribution methodology for trans GLA boundary emissions	MT, AB	
	5.3		Adapt existing carbon software	MT, AB	
	5.4		Baseline personal transport emissions calculations for London	MT, AB	
	5.5		Review freight transport emissions allocation methods	MT, AB	
	5.6		Development of methods to calculate freight transport emissions	MT, AB	
	5.7		Review of impacts of policy on transport emissions in London (baseline data)	MT, AB	
	5.8		Future look taking account of outputs from economic and land-use models	MT, AB	
6.5	**6**	**Emissions**		**SC**	
			Contract	SC	
	6.1		Agree sectors	SC	Econ, Landuse
	6.2		Complete inventory for London 2000-2005	SC	
	6.2		Emissions calculator spreadsheet	SC	
	6.3		Identify the appropriate programming language	SC	
	6.4		Learn enough of language to produce stakeholder tool	SC	
	6.5		Develop emissions scenarios consistent with socio-economic scenarios	SC	All
	6.6		Produce emissions component of Integrated Assessment tool	SC	
	6.7		Stakeholder Interviews	SC	All
	6.8		Analysis & Write – up	SC	
6.7	**7**	**Water Res.**		**CW**	
			Contract	CW	
	7.1		Deriving inter-annual variability of historic rainfall and PET	CW	
	7.2		Integrating the six GCM/RCM scenarios into EARWIG	CW	
	7.3		CATCHMOD simulations of	CW	
	7.4		Current naturalised flows for the four sub-catchments	CW	
	7.5		Current naturalised flows for the whole Thames catchment to Kingston	CW	
	7.6		Future naturalised flows for the four sub-catchments	CW	Climate Scenarios
	7.7		Future naturalised flows for the whole Thames catchment to Kingston	CW	Climate Scenarios
	7.8		Bayesian approach to producing a single probabilistic future flow series	CW	
	7.9		Adjustment of the flow output based on external factors	CW	Land use model, socio-econmic scenarios
6.7	**8**	**Flood**	*Being updated	**RD**	
	8.1		Review current developments in Thames flood risk analysis	RD	
	8.2		Demonstrate effects of land use policy on flood risk	RD	Landuse
	8.3		Implement flood impacts module	RD	
6.7	**9**	**Heat**	*Being updated	**RD**	
	9.1		Preliminary design	RD	
	9.2		Review	RD, LSHTM, UEA	
	9.3		Update design	RD, LSHTM, UEA	
	9.4		Develop climate component	UEA	
	9.5		Develop health component	LSHTM	
	9.6		Implement heat impacts module	RD	



D	Deliverable
WP	Working Paper
X	Links with other module
*	Full team meeting
G	Full team access grid meeting

Appendix L: Policy questions and variables

A list of all the policy questions that have been raised in stakeholder meetings is provided in Figure 6-4. This table also identifies the variable(s) that is changed in the UIAF in order to 'test' the policy question.

Figure 6-4 Table listing the policy issues identified by stakeholders and the policy variables they enact in the UIAF (those questions that can not be answered are denoted by 'n/a', those that can be answered through the SCORCHIO project are denoted as so), the variable type (Y, S, X, P, B) and the user control (where 'limited' means that the user will only be able to select pre-defined scenarios, and 'full' means the user will be able to edit the parameter value within its full range) [****]

Sector	Policy question	Variable	Variable type	User control
Economic	A.1) What will be the effect of carbon taxes and other economic instruments applied only within the GLA boundary on London's emissions and economy? Including:			
	a) Cap & trade schemes	London tax	S	Limited
	b) GHG taxes	London tax	S	Limited
	A.2) What will be the effect of carbon taxes and other economic instruments applied nationally or internationally on London's emissions and economy?	National tax	S	Limited
	A.3) How vulnerable is London's economy to climate impacts:		S	Limited
	a) In London?	London GDP		
	b) in the rest of the world?	Global GDP		
	A.4) What might be the effect of changes in tourism, due to economic or	Tourist	S	Limited

[****] Interaction with stakeholders is ongoing and these policy issues are expected to evolve in subsequent discussion, therefore this table should not be viewed as a final definitive statement.

	climate drivers?	revenue		
Development	B.1) What are the effects of land use planning on reducing vulnerability to climate impacts: 1.1) Floodplain policy 1.2) Brownfield policy 1.3) Higher density building 1.4) Greenbelt policy 1.5) Urban green space policy	Constraint fields and strength of constraint	P P Scorchio P P	Full Full Full Full Full
	B.2) What is the impact of changes in transport behaviour on land use change?	Modal distribution	P	Full
	B.3) What is the impact of changes to the transport network on land use change?	Transport network	P	Limited
	B.4) What is the spatial relationship between land use, planning policy and emissions?	Constraints & landuse and emissions models	P	Full
	B.5) What is the spatial relationship between land use, planning policy and heat?	Constraints & heat and emissions models	P	Full
Transport	C.1) What contribution does long distance travel make to London's emissions?	Travel survey	Y	Full

	C.2) Should City Airport stay where it is?	n/a	-	-
	C.3) What contribution of London's emissions are attributable to commuters and tourists?	Travel survey; airport activity etc.	P	Full
	C.4) What are the effects on transport emissions applied <u>only</u> within the GLA boundary of:			
	C.4.1) Charging	London road user charges	P	Full
	C.4.2) regulation	London regulation	P	Full
	C.5) What are the effects on transport emissions applied nationally or internationally of:			
	C.5.1) charging,	National road taxes and user charges	S	Full
	C.5.2) regulation	Vehicle usage	S	Full
	C.5.3) technology	Vehicle efficiency	S	Full
	C.6) What contribution does freight make to London's emissions?	Freight emissions vs. total	P	Full
	C.7) What are the benefits on freight emissions from:			

	C.7.1) taxation	Freight taxes	P	Full
	C.7.2) modal shift	Freight vehicle types	P	Full
	C.7.3) regulation	Regulation effectiveness	P B	Full Full
	C.7.4) local distribution facilities	Freight travel activity	S	Limited
Emissions	D.1) Can, and how might London achieve a 60% reduction in emissions?	All emissions variables	Y	Full
	D.2) What cumulative emissions reductions are required to achieve targets?	All emissions variables	P	Full
	D.3) What reductions in emissions can be gained from changing the energy generation portfolio and/or increasing generation and transmission efficiency?	Generation portfolio & efficiency	P	Full
	D.4) What is achievable and what are the benefits of de-centralised energy?	CHP and energy gen portfolio	P	Full
	D.5) What are the effects of economic instruments on reducing GHG and heat emissions?	Incentive effectiveness	B	Full
Impacts: Flooding	E.1) What will the fluvial and coastal flood risk be in the future?	Flood risk output	Y	Limited
	E.2) How much of this risk is a function of climate change, and how much	Flood risk	Y	Limited

	from socio-economic factors?	output		
	E.3) What decrease in the standard of flood defence could be justified?	Flood risk output	Y	Limited
	E.4) What is the reduction in flood risk from:			
	a) Raising existing flood defences	Crest height	P	Full
	b) Construction of an outer barrier	Hydrodynamic model	S	Limited
	c) Construction of flood storage areas		S	Limited
	d) Managed realignment		S	Limited
	e) River channel widening		S	Limited
	f) Land use management planning	Landuse model	P	Full
	E.5) What are the benefits of increasing the permeability of urban surfaces?	n/a	-	-
Impacts: Water resources	F.1) How bad will water scarcity get?	Water resources model	Y	Limited
	F.2) How can water scarcity be managed?			
	a) Reservoir capacity	Water storage	P	Full
	b) Leakage reduction	Leakage	P	Full
	c) Desalinisation	Desalinisation capacity	P	Full
	d) Catchment landuse change	Catchment percolation	S	Limited

	F.3) What can be achieved through demand management of water resources through:			
	a) Water pricing	Demand	P	Full
	b) Other incentives	Demand	P	Full
	c) Industry regulation	Demand	S	Full
	F.4) What are the implications of environmental water quality targets on water resources?	River abstraction capacity	S	Full
Impacts: Heat	E.1) How big could heat emissions from air conditioning get?	Air con. Emissions	Y	Limited
	E.2) Will the cooling effect of urban heat island adaptation measures have a detrimental effect on the winter benefits of the urban heat island at mitigating cold-related deaths?	??[††††]	-	-
	E.3) What are the effects of (*eg*. EU) air quality targets on emissions mitigation?	Emissions, total air pollutants	S or P	Full
	E.4) Are (and if so, how many) heatwave deaths are attributable to poor air quality	n/a	-	-
	E.5) Are there sustainable cooling solutions? (*eg*. tri-generation, ground source cooling)	Cooling portfolio	P	Full
	E.6) What are the benefits of urban heat island mitigation?	Scorchio	P	Full

[††††] This requires an appropriate cold vulnerability function which has yet to be agreed

Trans-sectoral issues (What can the IA provide that can *not* be answered by single model?)	F.1) *Adaptation and mitigation*: What are the implications of development scenarios and what does the future look like with/without adaptation and/or mitigation (in particular with reference to comparing the baseline with the London Plan)?	All adaptation & mitigation variables	-	-
	F.2) *Adaptation and mitigation*: do we adapt to water scarcity, heat and flooding without increasing emissions?	All adaptation & mitigation variables	-	-
	F.3) *Urban vs. national policies*: what are the risks and opportunities for London diverging from the global trajectory (eg. through imposing stricter carbon taxes, or investing heavily in emissions reduction schemes)?	Economic & mitigation variables	S	Limited
	F.4) *Attribution*: How much risk is attributable to climate change and how much to changed vulnerability?	Climate and socio-economic variables	S	Limited
	F.5) *Built environment*: What are building replacement rates for different types? What are the emissions associated with different building types and building adaptations/retro-fitting? What is the spatial relationship between energy and construction?	Scorchio and emissions model	-	-
	F.6) *Built environment*: What are the capacities and vulnerabilities of our infrastructure?	Impacts & adaptation variables	-	-
	F.7) *Planning*: Are there planning strategies that can reduce vulnerability and			

	emissions?	Landuse model	P	-
	F.8) *Planning*: How important is the decision sequence in planning?	All relevant parameters	-	-
	F.9) *Planning*: What spatial planning strategies are most robust to climate change?	All relevant parameters	-	-
	F.10) *Planning*: Are there limits to adaptation?	All relevant parameters	-	-
	F.11) *Uncertainties*: What are the greatest uncertainties in city-scale integrated assessment and how might these be reduced?	All relevant parameters	-	-
	F.12) *Future work*: What research is needed to improve the city-scale integrated assessment?	Not parameter specific	-	-

Appendix M: Skeleton code

Subsequent versions of this report will contain skeleton (or pseudo) code that:

- provides a formal overview of the Integrated Assessment calculation.
- has been tested to ensure the dimensionality of the vectors and arrays is correct.
- does not replicate the individual models – rather demonstrates that there are no logical inconsistencies in the process of communicating between the different models.
- is written in Matlab terminology and provided with comments to facilitate understanding.

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