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Assessment of climate change mitigation and adaptation in cities

Claire L. Walsh PhD
School of Civil Engineering and Geosciences, Newcastle University, UK
Richard J. Dawson MEng, PhD
School of Civil Engineering and Geosciences, Newcastle University, UK
Jim W. Hall PhD, CEng, FICE, FRSS
Professor, School of Civil Engineering and Geosciences, Newcastle University, UK
Stuart L. Barr PhD
School of Civil Engineering and Geosciences, Newcastle University, UK
Michael Batty PhD, CBE, FBA, FRS
Professor, Centre for Advanced Spatial Analysis, University College London, UK
Abigail L. Bristow MA, PhD
Professor, Department of Civil and Building Engineering, Loughborough University, UK
Sebastian Carney PhD
School of Environment and Development, University of Manchester, UK
Athanasios S. Dagoumas Diploma (Greece), PhD
Department of Land Economy, University of Cambridge, UK
Alistair C. Ford BSc
School of Civil Engineering and Geosciences, Newcastle University, UK
Colin Harpham PhD
Climatic Research Unit, University of East Anglia, Norwich, UK
Miles R. Tight PhD
Institute for Transport Studies, University of Leeds, UK
Helen Watters PhD
Institute for Transport Studies, University of Leeds, UK
Alberto M. Zanni DEA, PhD
Department of Civil and Building Engineering, Loughborough University, UK

Cities are faced with a number of sustainability challenges in the context of climate change. There is an urgent need to limit greenhouse gas emissions from cities if ambitious mitigation targets are to be met. Meanwhile, cities are vulnerable to the impacts of climate change unless adaptation plans can be put in place. The need to connect climate change adaptation and mitigation with broader assessment of sustainability is becoming increasingly recognised. This paper describes an urban integrated assessment facility developed by the Tyndall Centre for Climate Change Research, which simulates socio-economic change, climate impacts and greenhouse gas emissions over the course of the twenty first century at the city scale. The urban integrated assessment facility adopts a broad-scale systems approach to urban development and sustainability assessment. It incorporates a multi-sectoral model of the regional economy, hierarchical city-scale spatial interaction model and modules for assessment of climate impacts, adaptation options and greenhouse gas emissions. The paper demonstrates how the urban integrated assessment facility quantifies synergies and conflicts between adaptation to climate change and mitigation of greenhouse gas emissions in order to improve decision making and facilitate the development of portfolios of planning policies that together have a realistic prospect of achieving sustainable outcomes for cities.

1. Introduction

Urban areas occupy less than 2% of the Earth's land surface (Balk *et al*., 2005), but house just over 50% of the world's population, a figure that was only 14% in 1900 (Douglas, 1994) and one which is expected to increase to 60% by 2030 (UN, 2004). Urban activities release greenhouse gases (GHGs) that drive global climate change directly (e.g. fossil fuel-based transport) and indirectly (e.g. electricity use and consumption of industrial and agricultural products). As much as 80% of global GHG emissions are estimated to be attributable to urban areas (O'Meara, 1999). Cities are also potential hot spots of vulnerability to climate change impacts by virtue of their high concentration of people and assets.

Responding to climate change by mitigating carbon dioxide emissions and adapting to the impacts of climate change is placing new and complex demands on urban decision makers and engineers. Targets for mitigation of carbon dioxide emissions are now urgent and imply reconfiguration of urban energy systems, transport and the built environment. Adaptation of cities requires integrated thinking that encompasses a whole range of urban functions.

The aim of this paper is to demonstrate how some of the complex interactions between climate change and cities can be assessed and managed. First this paper describes some of the potential climate impacts that cities will face. It then discusses how cities should respond to climate change while addressing the issue of sustainability. Finally the paper shows that it is both possible and informative to look at cities in a quantified integrated way over a timescale of decades. The urban integrated assessment facility (UIAF), developed by the

Tyndall Centre for Climate Change Research, is proving to be of value in stimulating more integrated thinking about cities and informing complex decision making problems.

2. Climate impacts in urban areas

Globally, climate change is expected to lead to an increase in mean sea level and changes in frequency, intensity and spatial patterns of temperature, precipitation and other meteorological phenomena, such as wind and cloud cover (IPCC, 2007). Local and regional climate variability means that the magnitudes of different climate related impacts inevitably vary from city to city.

The type of impacts and their magnitude will differ according to the location of the urban area, but some key impacts, from a review of a wide range of sources (Dawson, 2007; DoH, 2008; Hunt and Watkiss, 2007; IPCC, 2007; Nicholls, 2002; Oke, 1982; Sanders and Phillipson, 2003; Stern, 2006; Wilby and Perry, 2006) are now highlighted. The most pressing issues of relevance to engineers seeking to adapt cities strategically are outlined below.

(*a*) Sea level rise (including the effects of changes to storm surges) will increase the risk of storm-surge flooding and rates of coastal erosion, thereby threatening beaches, coastal settlements and wetlands. Raised sea levels can also lead to saline intrusion into freshwater aquifers and impeded drainage of extreme flows in urban drainage systems and rivers.

(*b*) Water availability will decrease in many areas, with implications for water resources in terms of both quality (and concomitant implications for health and aquatic ecosystems) and availability for human consumption, industry and neighbouring agricultural areas.

(*c*) Urban heat islands are 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 replaces the cooling effect of vegetated surfaces by imperviously engineered surfaces with different thermal properties. Furthermore, anthropogenic sources (e.g. central heating systems, air conditioning, transport, industrial processes) emit heat directly into the urban area, while buildings and infrastructure increase surface roughness that can reduce wind speeds, convective heat loss and evapotranspiration.

(*d*) Air pollution may increase as warm, still days reduce air quality because high temperatures and ultraviolet light stimulate the production of photochemical smog, ozone and other compounds from traffic and industrial emissions and plants. This is aggravated in cities by buildings and infrastructure that increase surface roughness, which can reduce wind speeds, convective heat loss and evapotranspiration.

(*e*) Infrastructure damage from extremes, such as wind storms including hail and storm surges, floods from heavy precipitation events, landslides, tropical cyclones and heat extremes including fires and droughts, is likely to become more prevalent. Changing patterns of precipitation, heat and wind will place additional strain on infrastructure systems, leading to increased disruption for businesses and inhabitants.

(*f*) Health impacts may include changes to heat- and cold-related mortality, food- and water-borne disease, and vector-borne disease arising from higher average temperatures and/or extreme events. Effects are likely to see reduced cold-related deaths, but more heat-stress deaths. Higher ultraviolet (UV) exposure (from reduced cloud cover) will lead to increased incidences of cataracts and skin cancer. Warming and reduced water quality may potentially facilitate migration and establishment of vector- and water-borne diseases in new regions and increase incidences of food poisoning. More frequent extreme weather is likely to increase incidences of weather-related injury and loss of life.

(*g*) Biodiversity and urban ecology have already been affected by changes to temperature and precipitation that have resulted in exotic species (including pathogens and pests) establishing themselves in new areas. Species that can survive changes in climate may adapt by changing their phenology (e.g. flowering period, migration patterns). Sea level rise will squeeze the highly productive intertidal habitats and salt marshes.

(*h*) The urban economy may be affected in a diversity of ways. Extreme weather-related disasters such as the European heatwave of 2003 and hurricane Katrina in 2005 illustrated how the functioning of cities can be impacted in multiple and complex ways and can take a long time to recover fully. The impacts can lead to direct damage to infrastructure and other assets, but also lead to knock on loss of trade and disruption to business (Haimes and Jiang, 2001), although recovery from extremes can lead to a flurry of economic activity (e.g. (re)construction) (Hallegatte, 2008). In addition to impacting directly on the physical assets used within cities for economic production and/or services, climate change may impact the costs of raw materials and inputs to economic production, the subsequent costs to businesses, and thus on competitiveness (or comparative advantage) and wider economic performance of the city. Despite these potential risks, there are potential opportunities, for example in environmental businesses, increased tourism in temperate cities and reduced heating costs (GLA, 2002).

3. Broader issues of sustainability

Urban settlements are not isolated, interacting strongly with surrounding regions, and increasingly the rest of the world. This interaction occurs through complex flows of energy, information, transport, materials, food, waste and water.

Increasing global population and a trend towards more resource intensive lifestyles will continue to alter these flows. Many of the resources used in cities, particularly those related to agriculture, forestry, fisheries and so on are susceptible to climate impacts, such as land degradation, salinisation of aquifers, soil erosion and changed crop yields (although yields could be increased in many areas). Industries (including energy generation) are also vulnerable to water shortages and other climate hazards. Even those cities that are unlikely to experience the greatest climate change impacts may still find themselves vulnerable to resource shortages elsewhere in the world. Furthermore, as raw materials, design, production and selling of manufactured goods occur in multiple locations, emissions of GHGs from transportation can increase while emissions associated with manufacturing are displaced from the 'end-user'.

Climate change may also act as a driver for changing the behaviour of urbanites. Increased temperatures, rising sea levels and water shortages may lead to changes in behaviour and use of resources. This can lead to unnecessary use of energy-intensive adaptations such as air conditioning, pumped drainage or desalination plants. There are often important tradeoffs – such as the need to balance water demand for consumption, cooling in power plants and avoiding over-extraction, which can lead to a drop in water quality (all of which are aggravated under higher temperatures). Of course, these impacts are exacerbated by other drivers of urbanisation such as population increase and migration.

It is important to recognise that climate change on its own does not necessarily imply significant impacts and socio-economic change can be just as crucial in determining the magnitude of impacts (if not more so) as climate change (Hall *et al*., 2005). The vulnerability of urban areas to climate change is a function of social, economic and political processes. Determinants of vulnerability include (Adger *et al*., 2005; Allenby and Fink, 2005): economic well-being and stability (e.g. standard of living; rate of urbanisation); demographic structure of population, institutional stability (e.g. institutional 'memory'; corruption); strength of and reliance on public infrastructure (e.g. health expenditure; communication infrastructure; financial, transport, corporate and systems; degree of centralisation); global interconnectivity (e.g. trade balance; tourism); and natural resource dependence and regenerative ability of ecosystems. It is clear then that reducing vulnerability not only includes direct measures such as spatial planning but broader economic factors (such as diversification of supply chains) and, crucially, modes of urban governance.

Climate change and sustainable development have been addressed in largely separate circles, both in terms of research and policy. However, the need to connect the two is becoming increasingly recognised in the climate change literature (see Chapter 20 of IPCC, 2007). Climate change vulnerability, impacts and adaptation will influence prospects for sustainable development, and in turn, alternative development paths will not only determine GHG emission levels that affect climate change, but also influence future capacity to adapt to and mitigate climate change. Impacts of climate change are exacerbated by development status, adversely affecting the poor and vulnerable socio-economic groups. Within and between cities in different countries, there are often striking contrasts in the socio-economic groups that make up their populations. Thus in addition to the range of different potential climate impacts evident in a city and the associated mitigation and adaptation response, the challenge of striving towards sustainable development in each city is unique.

4. Responding to climate change: mitigation and adaptation

In general, engineering responses to addressing climate change fall into two categories:

(*a*) mitigation to reduce GHG emissions and enhance any processes (natural or artificial) that remove GHG emissions from the atmosphere
(*b*) adaptation to reduce the impacts of harmful changes and exploit potentially beneficial changes.

Both mitigation and adaptation seek to avoid the potential damages of global climate change, and they both seek to support the development of present and future generations in a sustainable manner. The Stern Review (Stern, 2006) stated 'Adaptation is the only response available for the [climate change] impacts that will occur over the next several decades before mitigation measures can have an effect'. However, the influence and incidence of employing them as climate policy instruments are different.

Benefits of mitigation activities will not be immediately recognised given the long residence time of GHGs in the atmosphere. Adaptation measures should be apparent sooner and in any case reduce the risks associated with extreme events. The benefits of mitigating GHG emissions are felt globally, although there may be local co-benefits associated with improved local air quality. Meanwhile, adaptation takes place on the scale of an impacted system; for example, sea defences will only benefit settlements and ecosystems directly protected by the defences. While sectors involved in measures of energy demand reduction span all sectors, the main sectors emitting GHGs are relatively few, primarily energy, transport, heavy industry and agriculture. Adaptation involves a much larger variety of sectors such as human health, water supply, urban planning and coastal management (Klein *et al*., 2005). The complexity of different actors and policies within these contrasting sectors, in addition to varying temporal and spatial scales of mitigation and adaptation, renders the development of integrated strategies difficult. In urban areas, mitigating and adapting to climate change involves complex interactions of citizens, governmental/non-governmental organisations and businesses (Hall *et al*., 2009).

5. Interactions between mitigation and adaptation

Undoubtedly a more informed understanding of the synergies, conflicts and trade-offs between mitigation and adaptation measures would contribute to a more integrated climate policy and more effective climate-proofing of urban environments (Dawson, 2007). McEvoy *et al*. (2006) highlight some of these interactions using the example of urban form. More compact settlements may reduce energy demand and transport emissions, yet the increase in built mass would intensify the urban heat island effect and pose problems for urban drainage. Intensification of the urban heat island effect coupled with predicted hotter summers would lead to an increased use of air-conditioning or an increase in city-dwellers using transport to leave the area; both would lead to an increase in emissions. In the case of urban drainage, predicted increases in intense rainfall and wetter winters coupled with urbanisation (increase in impermeable surfaces) would cause an increase in the risk of pluvial flooding; urban flood risk would be greater if coupled with fluvial flooding. Incorporation of green and blue space in urban design would go some way to reducing these two impacts by providing cooling and producing storage and infiltration, as well as providing opportunities for sequestering carbon and addressing social and potentially economic aspects of sustainable development.

There are a number of areas in the built environment where strategies for adaptation to climate change might have an adverse effect on GHG emissions and hence mitigation efforts – for instance, by the installation of energy-intensive air conditioning to cope with higher temperatures or desalinisation plants to enhance water resources. Many of the materials and engineering solutions for adaptation may have significant energy implications. On the other hand, some mitigation measures might increase vulnerability to climate impacts, for example, cavity wall insulation, which is a maladaptation to flood risk.

Despite the differences between adaptation and mitigation strategies, both are essential in reducing the risk of climate change, hence opportunities are being sought to develop synergies between the two options. Synergies in climate policy are created when measures that control atmospheric GHG concentrations also reduce the effects of climate change, or vice versa. A classic example is the planting of trees in urban areas: they sequester carbon as they grow and they reduce urban heat stress in the summer (although certain species may be vulnerable to temperature increase).

6. Integrated assessment of climate change in cities

While the objectives of mitigation and adaptation are clear and well aligned with the broader aims of sustainable development, the process of designing transitions to sustainability in urban areas is much more complex (Hall *et al*., 2009). Within cities interactions occur through land use, infrastructure systems and the built environment. Viewing cities as systems avoids a narrow approach to problems and helps avoid conflicts between the objectives of adaptation and mitigation, as well as between economic growth and sustainable development. Interactions between different urban functions and objectives occur at a range of scales from individual buildings to whole cities and even beyond. Such also occur at a wide range of timescales. Figure 1 shows a sample of the processes whereby climate influences urban function and urban functions interact, most of these urban functions emit carbon dioxide. Climate drivers need to be considered alongside other processes of long-term change such as the economy, demography and technological and behavioural change. By breaking down some of these complex interactions at a range of spatial and temporal scales a better understanding can be sought. For example, using spatial interaction models of travel journeys within and outside cities can help to explain where people choose to live; regional economic models help to describe relationships between different economic sectors; and the existence of well-established impact models is useful for water resources and flooding. However, it is only by considering these insights in an integrated manner that they may inform effective decision making by providing a better understanding of the potential direct and indirect consequences of decisions, and aid development of portfolios of measures that aim to address a number of different challenges in a synergistic way.

7. The Tyndall Centre urban integrated assessment facility

The Tyndall Centre for Climate Change Research has developed an urban integrated assessment facility (UIAF) which simulates the main processes of long-term change at the scale of whole cities. Figure 2 shows the overall structure of the UIAF. The UIAF couples simulation modules within a scenario and policy analysis framework. The UIAF is driven by global and national scenarios of climate and socio-economic change, which in turn drive regional economic and land use change models. Simulations of climate, land use and socio-economic change inform analysis of carbon dioxide emissions from energy, personal and freight transport and impacts of climate change focusing on heat waves, drought and floods. An integrated assessment tool provides the interface between the modelling components, their results and the end-user, enabling a number of adaptation and mitigation options to be tested within a common framework. This analysis uses the city of London as a case study and simulates up to the year 2100.

The various models that are integrated in the UIAF are now briefly described.

7.1 Regional economic modelling

The multisectoral dynamic model (MDM) (Barker and Peterson, 1987; Junankar *et al*., 2007) was used to provide quantified economic scenarios (employment, gross value added and energy demand) that are the starting point for analysis of vulnerability and GHG emissions. The model is a coupled macro-economic model of the whole economy, but is multi-sectoral, so predicts output from and employment in 42 different industrial sectors. As it is a model of growth and fluctuations over the medium and long term it is suited to providing internally consistent scenarios for the integrated assessment. The model is dynamic, providing intermediate results at time-steps over the simulation period. Inputs to the model are baseline projections of long-term growth and population, as well as past observations of relationships between different industrial sectors.

Three main scenarios were developed representing baseline, low- and high-growth scenarios based on GDP growth rate. The 42 sectors were aggregated into eight categories. Trends of employment and economic activity of the eight sectors for the baseline, low- and high-growth scenarios were calculated. In applying the UIAF, a range of growth rates and scenarios were considered. For clarity in this paper all projections assume London is predicted to have a growth rate of 2.5–3% up to 2060, which decreases steadily to 1.4% by 2100. Banking, finance, business and science-based industries are expected to grow most rapidly, with heavy industry diminishing.

7.2 Projections of land use change

Future vulnerability to climate change and demand for energy services that emit GHGs are closely linked with land use

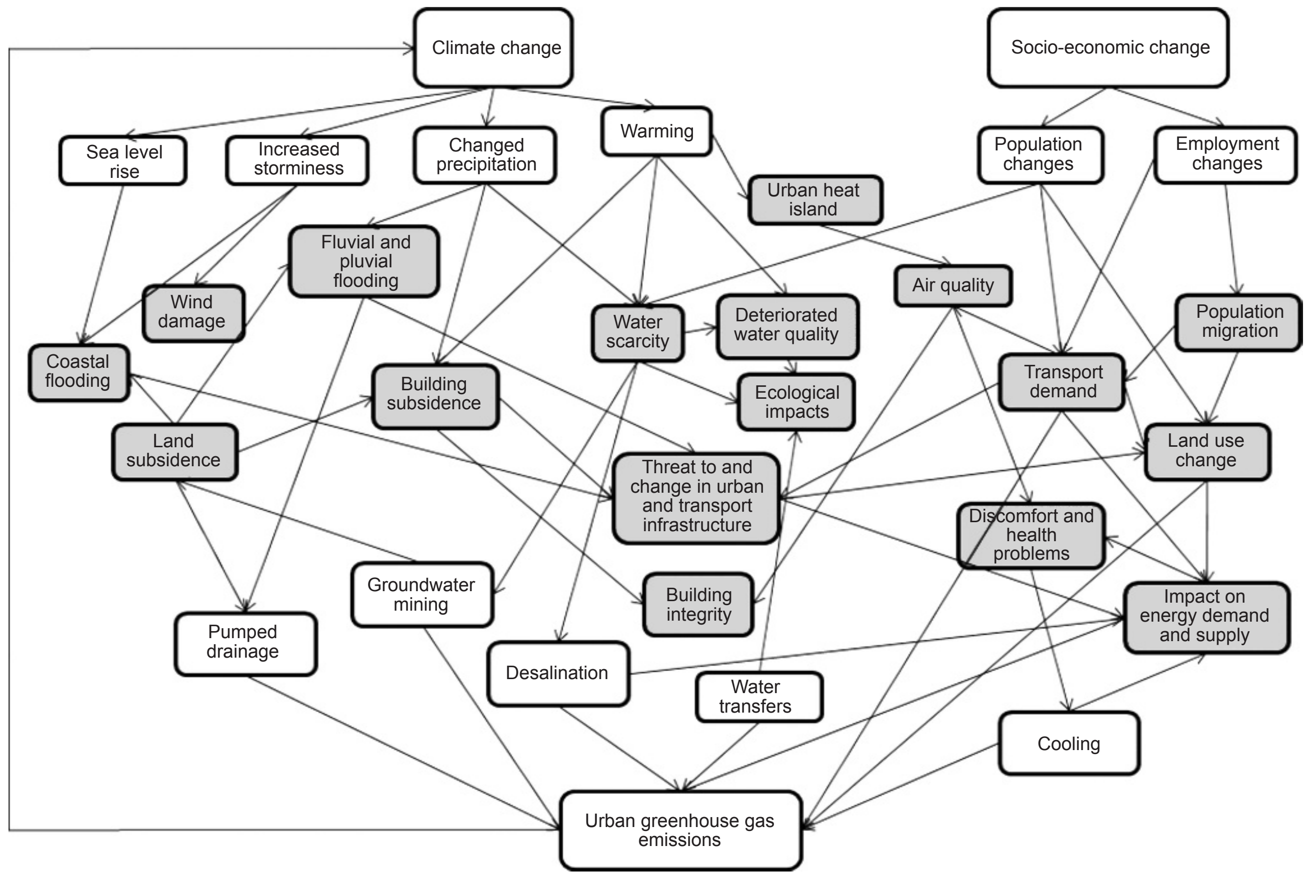

Figure 1. A sample of the many complex interactions and interdependencies between climate change, adaptation and mitigation in cities

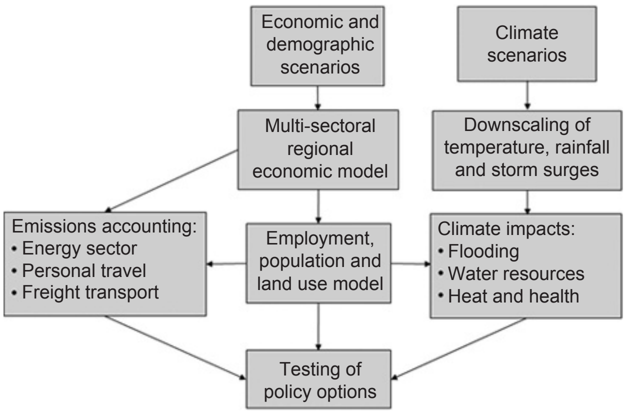

Figure 2. Overall structure of the UIAF

patterns in urban areas (Hall *et al*., 2009). A land use model has therefore been developed in order to simulate spatially explicit climate impacts, the resolution of which may vary depending on the process or impact considered. The methodology developed is based on the Lowry (1964) land-use/transport model using attractors, in the form of employment opportunities and available land, and constraints in the form of transport costs and planning restrictions, to distribute predicted population and employment changes. Changes can then be mapped to physical land-use variations using a distribution function constrained by planning and policy restrictions. A number of land use planning policy packages have been developed and tested which include infrastructure development, transport options and planning incentives. Analysis of the spatial interaction model occurs at the ward scale. Figures 3(a)–3(c) show the spatial distribution of population within the Greater London and Thames Gateway area. Figure 3(a) indicates current population distribution; Figure 3(b) indicates population distribution if development was unconstrained apart from development being prohibited on greenbelt land; Figure 3(c) promotes brownfield land development as the main driver: that is, previously developed land is filled in preference to any other land type. However, for climate impacts analysis such as flood risk, higher resolution scenarios are required. For example, a module has been developed that enables a 100 m grid to be created. Figure 4 shows existing and future land use in East London on a 100 × 100 m grid under the baseline land use paradigm.

7.3 Climate impacts: testing adaptation options

Climate impact analysis focuses on the three most important potential impacts of climate change in London: heat waves, water scarcity and flooding. For each, both probability and consequences of harmful climate-related events were considered. Here an overview is provided only of the analysis of water scarcity. The assessment methodology involved simulations of rainfall under current and future climates UKCP09 (http://ukclimateprojections.defra.gov.uk) being assessed with a hydrological model and a water resource system management model to analyse present and future water resources available to London. Scenarios for water supply were evaluated alongside scenarios of demand and management of existing and new resources. The frequency of emergency drought orders (i.e. deployment of standpipes, rota cuts or water tanks) was used to assess demand change based on population growth predicted by the economic modelling and future climate conditions (Figure 5). Results show that socio-economic change – that is, changes in demand – is a significant driver of water vulnerability, which increases further under projections of future climate change.

Subsequent analysis shows the necessary combination of demand and supply changes required to maintain existing levels of service. Demand reductions are measured relative to the current average demand of individuals and the industrial and commercial sectors, as well as leakage. Supply construction could be increased through construction of reservoirs, reuse of waste water, desalination plants or inter-basin transfers. Figure 6 indicates that increased storage capacity has the potential to compensate for increasingly intermittent flows projected by climate scenarios, yet construction of feasible storage capacity alone will not be sufficient to adapt to climate change and supply an increasing population unless demand is reduced.

Water resource systems already consume large quantities of energy. Some adaptation options such as inter-basin transfers and desalination plants would intensify energy consumption unless energy is obtained from renewable sources. On the other hand, demand reduction measures can reduce energy consumption, for example by reducing the amount of water that is pumped, treated and heated.

7.4 Emissions accounting

The estimation of GHG emissions within the integrated assessment is also driven by the demographic and economic projections described earlier. Emissions from energy use in London for different economic sectors (excluding transport) and for the domestic sector assuming high population growth projection are projected to 2050 (Figure 7). This baseline projection assumes energy demand per capita and/or unit of economic activity remains constant and there are no changes to energy generation mix and efficiency. Rising domestic, financial, retail and other emissions are a result of increases in population and employment in those sectors, while primary and construction emissions decrease. The analysis also enables projections of emissions reductions from different sectors and electricity generation by different technology types that are

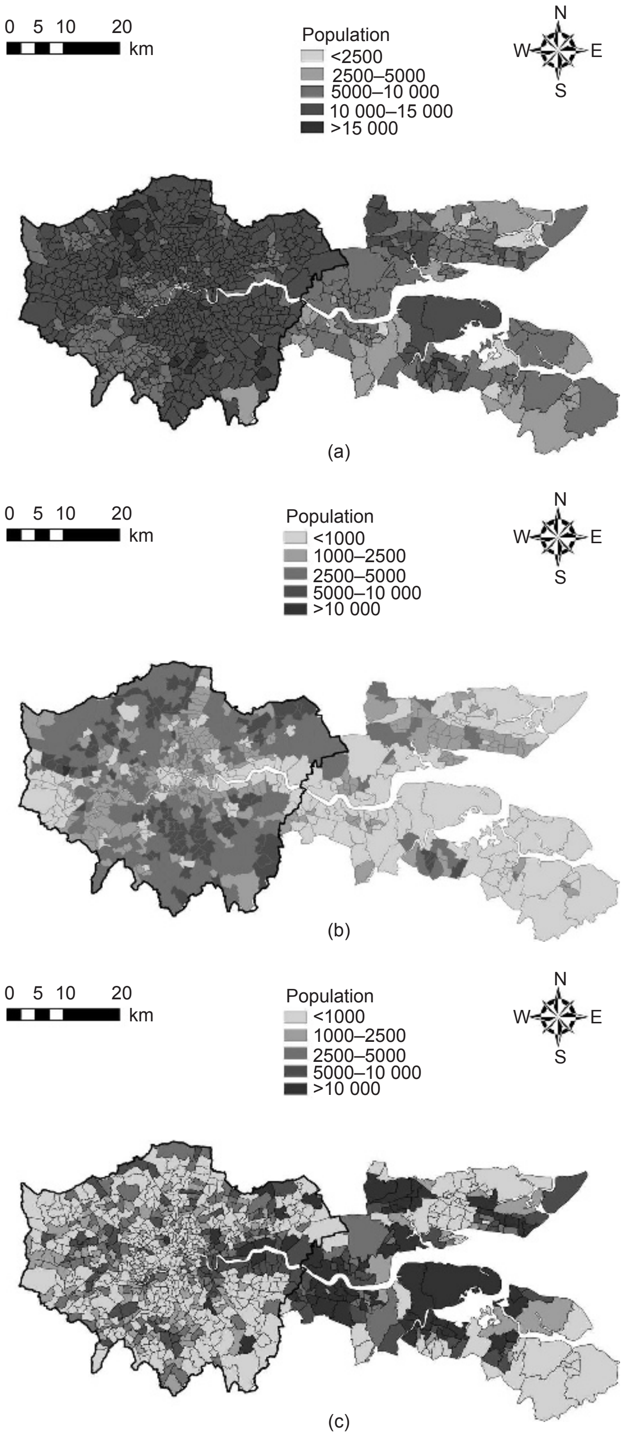

Figure 3. Population distribution within the Greater London Authority and Thames Gateway area: (a) currently; (b) growth in population under an unconstrained development paradigm 2005–2100; (c) growth in population under a paradigm to promote brownfield land development 2005–2100

necessary to achieve specified carbon dioxide emissions reduction targets, for example 80% cuts sought by the Department of Energy and Climate Change's Low Carbon Transition Plan (HM Government, 2009).

The UIAF also includes modules that generate GHG emissions scenarios from personal and freight transport which use travel survey data to understand existing travel patterns. Policies' relation to infrastructure (e.g. loading bays, preferential lanes), regulation (e.g. delivery restrictions, road user charges), efficiency (e.g. driver behaviour) and modal shifts have been tested. Results show that although technological and efficiency measures can mitigate increases in GHG emissions, substantial reductions relative to today are only achievable by also managing demand (Watters *et al*., 2007; Zanni and Bristow, 2008).

7.5 Supporting decision making

The analysis of the various modules is brought together in an integrated assessment tool. The more computationally efficient modules (e.g. the land use model) are implemented within the platform whereas the more computationally demanding modules, such as the economic and climate analysis, are run off-line and their results included in the user interface. The integrating user interface provides the flexibility to set scenarios, specify policy options and visualise results.

Throughout the research programme there has been regular interaction with a range of stakeholders on specific research questions. Notably the research team has worked with the Greater London Authority to test a range of land use planning policy options proposed as part of the London Plan (GLA, 2004). Quantified projections of the implications of alternative planning policies can be used to evaluate the impacts of policies and identify desirable combinations of policy options. Specifically, the range of transport options for the future scenarios and assessments of a range of land use planning policies that may be considered as part of the London Plan have been considered. The deliverables of the analysis are in the form of new quantified projections of the implications of alternative planning policies, which may be used to evaluate the impacts of the policies and identify desirable combinations of policy options.

8. Conclusions

A foremost challenge facing urban planners and engineers today is the need to deliver plans, designs and strategies to reduce GHG emissions and to adapt our urban areas and infrastructure systems to be resilient to the various impacts of climate change. In order to achieve this, climate change scenarios and uncertainties need to be embedded in everyday engineering solutions. Both mitigation and adaptation measures are required. However, it is important to recognise that

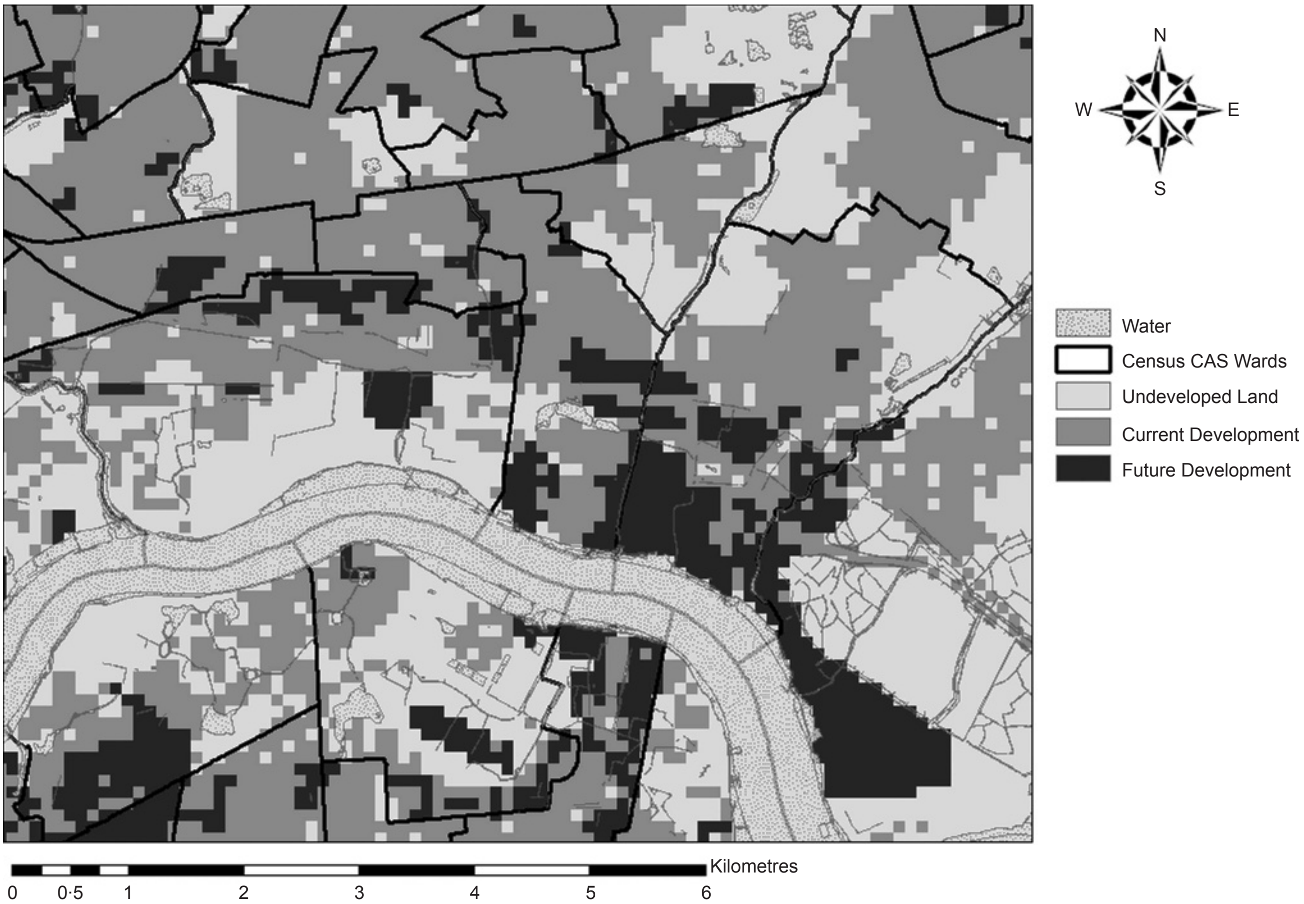

Figure 4. Existing and future land use in East London on a 100 × 100 m grid under the baseline land use paradigm

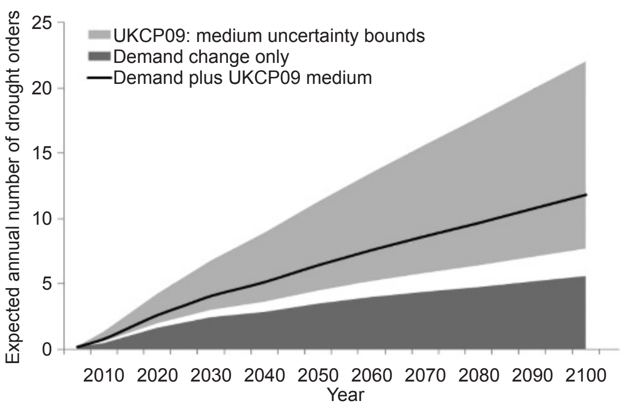

Figure 5. Expected annual number of drought orders under changing demand only compared with demand plus UKCP09 medium climate change scenario

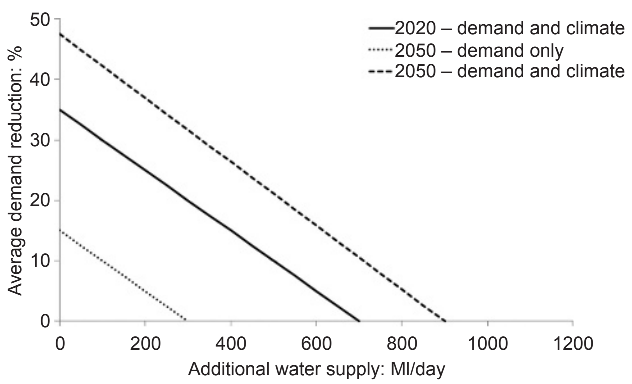

Figure 6. The reduction in water demand or additional supply required to maintain present day level of service (in terms of expected annual number of drought orders) in 2020 accounting for demand and climate change; in 2050 accounting for demand change only; and in 2050 accounting for demand and climate change

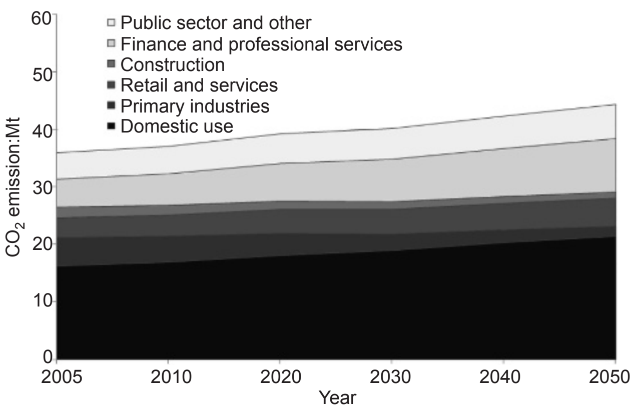

Figure 7. Emissions from energy use in London for different economic sectors (excluding transport) and the domestic sector assuming a high population growth projection

their implementation varies and a more informed understanding of their synergies, conflicts and trade-offs is essential in developing a more integrated climate policy and integrated portfolio of effective management options for our urban environments. Integrated responses to the challenges of urban areas are essential, yet the complexity of integrated approaches may hamper effective decision making. Methods and tools that facilitate and inform integrated assessment can help design these integrated responses.

The need to consider climate change alongside the broader issue of urban sustainability has prompted models like the UIAF described in this paper. The assessment models incorporated in the UIAF simulate the main processes of long-term change in urban demography, economy, land use, climate impacts and GHG emissions within a coherent assessment framework at the scale of whole cities. Although this programme of research has focused on London, the climate challenges addressed are recognisable to all UK local authorities. Moreover, the modelling tools use nationally available datasets so could readily be transferred to other UK cities as the demand for quantified tools to assess sustainability of urban areas increases. However, the analysis has made some simplifying assumptions about processes and interactions that have been included in this broad-scale assessment. In particular, the potential impacts of climate change upon the urban economy and land use has not been considered. A recently funded Engineering and Physical Sciences Research Council (EPSRC) project, Arcadia (Adaptation and Resilience in Cities: Analysis and Decision making using Integrated Assessment) will tackle this interaction. Indeed, whereas the UIAF has demonstrated the capability to test adaptation and mitigation policies, the next stage is to develop integrated portfolios of options, along with strategies for their implementation through time in the transition to decarbonised and well-adapted cities. More rigorous examination of uncertainties is required to develop robust portfolios of policy options for vulnerable urban areas.

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