



Urban climate change adaptation pathways for short to long term decision-making

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Thesis presented for the degree of Doctor of Philosophy at the University of Oxford

Linacre College

Trinity Term 2016

Abstract

Climate resilience is increasingly an attribute of competitive global cities. Cities that are most responsive to change will continue to prosper. To achieve this, governance structures and decision-making approaches that promote flexible and/or robust adaptation action are required. This thesis introduces a framework for urban adaptation planning that links medium-term risk management with the development and appraisal of long-term adaptation pathways. A long-term plan informed by the appraisal of a range of plausible pathways provides the opportunity to retain the flexibility to respond to future uncertainties, whilst also demonstrating how a city could manage future climate risk. This provides stakeholders with confidence that long-term risk is adequately considered, even if there is not a need to act immediately.

To demonstrate how adaptation pathways can support adaptation decision-making in an urban system, the approach and methods developed as part of this thesis are applied in London. Adaptation pathways in response to water scarcity, surface water flood and heat risk were developed, and their appraisal presented as pathways diagrams. These diagrams provide a visual representation of the sequencing of decision points and plausible adaptation actions that may be implemented in the future. Pathways diagrams present climate risk and adaptation information for decision-makers in a salient and actionable manner. The pathways responding to individual risks in London are then brought together to demonstrate how an integrated assessment framework may be used to appraise city-scale adaptation pathways that respond to multiple climate risks.

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The growing emphasis within adaptation planning on approaches that can react flexibly to change increases the need to better understand the dynamics of climate risk and embed learning about the effectiveness of adaptation actions. To complement the pathways and adaptation decision-making research presented in this thesis, a framework that links adaptation monitoring and evaluation (M&E), risk assessment and decision-making is presented and explored to highlight the potential benefits of, and mechanisms for, adaptation M&E to inform and strengthen iterative risk-based adaptation planning. Demonstrated for the Thames Estuary, where concepts of adaptation planning have been pioneered but the opportunities of linking to monitoring and evaluation have not been extensively explored, we show how the framework can highlight actions and factors that are contributing to improving adaptation outcomes and those that require strengthening.

This thesis contributes to the literature on urban climate change adaptation planning under conditions of uncertainty. This thesis also contributes to the evidence base needed to justify long-term planning and realise the benefits of climate risk reduction through the implementation of flexible, long-term integrated urban adaptation plans.

Keywords: Climate change adaptation; adaptation pathways; decision-making under uncertainty; water supply; heat risk; flooding; integrated urban planning

Publications

The work presented in this thesis has been submitted to the following peer reviewed journals:

Kingsborough, A., Hall, J. & Pringle, P. Submitted. Closing the adaptation loop: demonstration of an integrated framework to link monitoring and evaluation with risk assessment and decision making. *Climatic Risk Management* [under review].

Kingsborough, A., Borgomeo, E. & Hall, J. 2016. Adaptation pathways in practice: mapping options and trade-offs for London's water resources. *Sustainable Cities and Society*, pp. 386-397. 10.1016/j.scs.2016.08.013.

Kingsborough, A., Jenkins, K. & Hall, J. W. 2017. Development and appraisal of long-term adaptation pathways for managing heat-risk in London. *Climate Risk Management*. 10.1016/j.crm.2017.01.001.

Kingsborough, A., Jenkins, K., Hall, J. W., Reeder, T., Glenis, V., Taylor, J. & Mavrogianni, A. Submitted. Urban adaptation pathways: demonstration of an integrated approach in London. *Urban Climate* [under review].

For each of the publications I have collaborated with co-authors, as identified above. This has enriched the DPhil process, strengthened academic relationships and it has allowed me to address the breadth of issues required to effectively address theoretical and practical challenges in an urban setting. In each case, I undertook the majority of the work. I was responsible for the development of the key concepts and ideas, analysis of results and writing the papers.

Acknowledgements

This thesis was motivated by the observation that, in practice, many adaptation decisions were often informed by little more than gut feeling, and by my desire to explore what good adaptation decision making might look like. I would like to thank my supervisor Professor Jim Hall who helped me to unpack ideas, encouraged me to think broadly and embrace the complexity of urban systems, continued to remind me of the value of demonstration, and at times the need to just get on with it.

Thank you to the Sir John Monash Foundation who provided me with the funding necessary to embark on the DPhil journey and for welcoming me into their community of scholars.

Many thanks to Tim Reeder, a ‘champion of pathways’ if ever there were one, for his wise council and willingness to discuss ideas and their application. Thank you to Alex Nickson, Matt Thomas and colleagues at the Greater London Authority, the London Climate Change Partnership and Thames Water for constructively engaging with this research and providing a reality check when required. Thanks to Vassilis Glenis whose many model runs facilitated the availability of the latest climate information. My gratitude to Jonathon Taylor and Anna Marrogianni for supporting the cross-institutional collaboration that is required to do integrated research effectively. Thanks to Paddy Pringle for the constructive ‘adaptation discussions’ and for the encouragement to consider multiple perspectives. Many thanks also to Katie Jenkins for having the patience to get me up to speed on the modelling front, for her

constructive approach to problem solving and for her enthusiasm for me to continue to push this area of research forward.

Thank you to Roger Street and Cynthia Rosenzweig for the wise advice, pushing for this thesis to be the best it could be and for the enjoyable and rigorous discussion.

Thank you to the Environmental Change Institute for providing a rich learning environment and being home to many fascinating conversations. Thanks to Edoardo Borgomeo for his willingness to help, friendship and Italian travel advice. Thanks also to my fellow Oxford Geography DPhil students with whom I have shared the trials and tribulations of graduate student life as well as the odd pint, especially Chase, Abrar, Sisi, Scott and Kate. Thanks to my fellow residents of Paradise Island, particularly Mike, Raghav, Matt, Andreas, Rob, John and Alex, who ensured there was a standing offer for a coffee or beer, to mull over problems big and small.

Thank you to my family who have always encouraged my curiosity and supported me in pursuing my ambitions, even when they have taken me far from home. And thanks especially to Henry for keeping everything in perspective and Alice for your company during the final edits. The final thank you goes to Sally for supporting our return to student life, for your willingness to participate in innumerable conversations about adaptation, for reading drafts and providing thoughtful advice, for your confidence in me and for insisting that holidays are a good thing: without you this thesis would not have been possible.

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Acronyms

ASC	Committee on Climate Change Adaptation Sub-Committee
CATCHMOD	A rainfall runoff hydrological model
CDD	Cooling degree days
CIBSE	Chartered Institute of Building Services Engineers
EA	Environment Agency (UK)
EAD	Expected Annual Damages
EnergyPlus	A building energy simulation model
GI	Green infrastructure
GLA	Greater London Authority
GW	Gigawatt
HadCM3 GCM	Hadley Centre Coupled Model, version 3 Global Circulation Model
IPCC	Intergovernmental Panel on Climate Change
IRAS-2010	Interactive River-Aquifer Simulation Model 2010
JJA	June, July, August
kW	Kilowatts
L/p/d	Litres per person per day

LCCAS	London Climate Change Adaptation Strategy
LCCP	London Climate Change Partnership
LRR	London Risk Register
LWRZ	London Water Resource Zone
M&E	Monitoring and Evaluation
MBF	Mean Building Factor
MI/day	Mega litres per day
MSL	Mean Sea Level
NYC	New York City
PET	Potential Evapotranspiration
PHE	Public Health England
PLP	Property level protection
PV	Present value
SRES	Special Report on Emission Scenarios
SUDS	Sustainable Drainage Systems
SWF	Surface water flood
TE2100	Thames Estuary 2100 project
Tmax	Maximum temperature
Tmin	Minimum temperature

TW	Thames Water
UHI	Urban Heat Island
UIAF	Urban Integrated Assessment Framework
UK	United Kingdom
UKCP09	The United Kingdom Climate Projections 2009
US	United States of America
WG	Weather Generator
WRMPs	Water Resource Management Plans
WSUD	Water sensitive urban design

1 Introduction

Climate change is one of the most significant challenges of the 21st century faced by the global community. Increasing climate risk will have wide-ranging impacts on populations, the environment, infrastructure and economies (IPCC, 2014). Climate risk is a function of the probability and consequence of the hydro-meteorological hazards that are increasing due to climate change (IPCC, 2012), and the vulnerability and exposure of populations and assets. Rising temperatures and sea levels and the increasing frequency and severity of floods, storms and droughts, increase the frequency and severity of climate hazards. Climate change adaptation can limit the long-term negative impacts of climate change. Adaptation is a process of adjusting systems, in response to actual or expected climatic hazards or impacts, to moderate harm or exploit opportunities (IPCC, 2007). Planned adaptation includes the identification and implementation of measures and strategies that contribute to delivering adaptation actions and building adaptive capacity (UKCIP, 2010).

More than half the world's population lives in cities, and global trends indicate that strong economic incentives continue to drive humanity to urbanise (UN, 2012). Cities worldwide are hubs of creativity and economic development, yet at the same time, cities concentrate exposure to climate risks (IPCC, 2012). Adapting to climate change in cities worldwide is an important issue for governments to address (Rosenzweig et al., 2015, Hallegatte and Corfee-Morlot, 2010, Hunt and Watkiss, 2010).

The concentration of people and infrastructure, and cities' key role in critical economic, political and social processes magnifies climate risk (Birkmann et al., 2010). Many cities have established institutional and governance mechanisms to identify and manage social, economic, infrastructure and environmental risks. However, these were predominantly developed to manage existing risks, despite strategic urban decisions, particularly those related to spatial planning and infrastructure, having long-term implications. Moreover, risk management arrangements have tended to be implemented on an *ad hoc* basis, without systematic analysis of the risks to which cities are exposed. Such existing mechanisms do not account for the transient nature of a changing climate (Hallegatte, 2009) and they would be complemented by long-term approaches that enable governments to more effectively consider future climate risk. The complexity of interactions and challenges that cities face, demands that urban decision makers develop and utilise tools, strategies and policies to manage a broad range of on-going and emerging socio-economic, environmental and infrastructure challenges (Hallegatte and Corfee-Morlot, 2010). Increasing climate risk demands that cities implement a proportional response (Hall et al., 2012b) that increases their cities' resilience (Georgeson et al., 2016, Rosenzweig et al., 2015).

Resilience is widely considered as the capacity of a system to manage disturbance by resisting change, recovering from change, or adapting and benefiting as a result of change (Helfgott, 2014). This is consistent with the definitions of urban resilience adopted by New York City and 100 Resilient Cities. The former define resilience as being (i) able to bounce back after change or adversity, and (ii) capable of preparing for, responding to, and recovering from difficult conditions (NYC, 2013). 100 Resilient Cities defines resilience as 'the capacity of individuals, communities, institutions,

businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience’ (2015).

The ability to adapt is therefore considered a property of a resilient system. Adaptation may be incremental in response to proximate changes in risk, or, transformational in response to broader systemic change (Park et al., 2012, Pelling, 2011). Transformation refers to a fundamental change in the identity of a system, such that the original system is untenable and becomes something else, relative to the way in which the system was original defined (Helfgott, 2014, Park et al., 2012, Walker et al., 2004). Transformational change will be required when adaptation limits are exceeded (Dow et al., 2013, Kates et al., 2012).

As identified by Park et al. (2012), if the key difference between incremental and transformational change is the ‘extent’ of change, there lies a continuum between incremental and transformational adaptation (Thornton and Manasfi, 2010) and both processes may occur simultaneously (within nested systems). As demonstrated by Park et al. (2012) and Wise et al. (2014), ideas of transformation can be aligned with pathways based approaches, but as Wise et al. (2014) further recognise, to meaningfully consider transformation there is a need to for pathways to consider ‘broader and systemic change to social and political regimes’. It is outside of the scope of this thesis to explicitly consider changes to social and political regimes in London¹ or the differences between incremental and transformational adaptation.

¹ Exploratory scenarios and back casting may be more appropriate methods for exploring futures that are fundamentally different from the present (Vervoort et al., 2014).

This thesis aims to improve long-term urban climate change adaptation planning through the development of new methods and approaches to support current adaptation decision-making. The objectives of the thesis are to demonstrate:

- How adaptation pathways can support urban adaptation decision-making, within an overall framework for adaptation planning;
- How a framework linking adaptation monitoring and evaluation (M&E), risk assessment and decision-making may be used to improve adaptation planning;
- How quantified risk assessment can be used to appraise the effectiveness of long-term urban adaptation pathways; and
- The development and appraisal of an integrated adaptation pathway in response to multiple climate risks.

The complexity of urban adaptation planning increases the need for empirical demonstrations of how theoretical approaches can be used in practice (Lemos et al., 2012). Meaningful consideration of ‘resilience’, ‘adaptation’ and/or ‘transformation’ requires a clear understanding of: (i) the system these terms apply to; (ii) the disturbance a system is responding to; (iii) for whom such definitions apply; (iv) what constitutes a desirable or acceptable outcome; and (v) over what time frame such processes may occur (Helfgott, 2014). The approaches developed in this thesis are applied to London. By the middle of the century London is projected to experience warmer and wetter winters; hotter and drier summers (LCCP, 2012b); increasingly intense rainfall events and heat waves (Murphy et al., 2009); and increases in fluvial and surface water flood risk (EA, 2012, GLA, 2009, Wilby and Keenan, 2012). As the capital and economic engine of the UK, London has a high level of climate risk. London has demonstrated international leadership in city-scale climate change

adaptation, and a number of adaptation initiatives have been developed that could be expanded upon in this research. Stakeholders in London have demonstrated a willingness to explore new and innovative approaches to adaptation (Nickson et al., 2011). Much of the research for this thesis was undertaken in consultation with stakeholders to develop decision support tools that were credible, salient and potentially actionable. The scope and nature of the stakeholder interactions undertaken as part of this research and lessons learned are discussed in Appendix C.

Developing a long-term adaptation plan requires a sequential approach to decision making. A long-term plan include reduces the likelihood of mal-adaptation and undesirable lock-in, increases awareness of the dynamic nature of the climate system, and supports to the political and business case for integrating flexibility into infrastructure planning (Ranger et al., 2013, Payo et al., 2015).

Early examples of sequential decision-making in the decision theory literature explore the use of decision trees. Decision trees provide a structured way of dealing with sequential decision problems. The tree contains event nodes with uncertain outcomes and decision nodes that characterise the choices available to a decision maker (French, 1986, Lindley, 1985, Hammond et al., 1998). Sequential decision-making may explore whether it is worth investing in the present to keep options open for the future through real options analysis (Woodward et al., 2011). Decision trees and real options analysis rely on probabilistic characterisation of uncertainties (Simpson et al., 2015).

Long-term adaptation planning, however, is subject to deep uncertainty, which reduces the effectiveness of traditional decision processes based on finding an optimal solution evaluated with the best estimate of the future conditions (Hallegatte, 2009, Bankes, 2002). Conditions of ‘deep uncertainty’ occur when it is not possible to effectively

characterise probabilities with reasonable confidence (Lempert and Collins, 2007, Spiegelhalter and Riesch, 2011, Lempert et al., 2003). Approaches to decision making under deep uncertainty emphasise the identification of options that perform acceptably well, rather than those that are optimal for a given set of conditions (Hallegatte, 2009). A relative lack of sensitivity to assumptions or uncertainties may be used as an indicator of ‘robustness’ (Lempert et al., 2006, Groves and Lempert, 2007). Robust satisficing may be used to find solutions that perform acceptably well over a wide range of possible conditions (Ben-Haim, 2006).

The increasing acknowledgement that deep uncertainty is part of long-term decision-making has given rise to the development of a range of approaches for decision making under deep uncertainty (Kwakkel et al., 2016, Maier et al., 2016, Walker et al., 2013). These include Info-Gap Decision Theory (Ben-Haim, 2006), Decision Scaling (Brown et al., 2011b), Robust Decision-Making (Lempert et al., 2006, Groves and Lempert, 2007, Lempert et al., 2013), and Many Objective Robust Decision-Making (Matrosov et al., 2015, Kasprzyk et al., 2013). Robust Decision Making (RDM) was perceived to primarily be a tool for developing ‘static’ plans (Walker et al., 2013), however, this changing with the recent use of RDM to produce ‘adaptive’ plans (Kwakkel et al., 2016).

Sequential decision-making approaches can incorporate probabilistic information or they may be used to guide decision making under deep uncertainty (Simpson et al., 2015). An adaptation pathways approach may be used to inform sequential decision-making under deep uncertainty (Haasnoot et al., 2013, Reeder and Ranger, 2011, Wise et al., 2014). As a response to deep uncertainty, a pathways approach aims to build flexibility into a decision or strategy by sequencing the implementation of actions over

time so that the system adapts to changing social, environmental and economic conditions and options are available to respond to a range of plausible future conditions (Haasnoot et al., 2012, Hallegatte, 2009, Walker et al., 2013).

Pathways approaches acknowledge that to achieve strategic objectives, multiple decisions may need to be made in sequence over long time horizons and that societal preferences and decision makers' attitudes may change as outcomes are realised (Haasnoot et al., 2013). Adaptation pathways seek to ensure that planning and decision-making processes are robust, rather than focussing on the robustness of an individual decision or plan (Walker et al., 2013).

An adaptation pathways approach was first applied to planning for estuarine flood risk in London (Ranger et al., 2010b), and has subsequently been used in a range of contexts internationally (Barnett et al., 2014, Câmpeanu and Fazey, 2014, Fazey et al., 2016, Haasnoot et al., 2013, Haasnoot et al., 2012, Park et al., 2012, Rosenzweig and Solecki, 2014, Wise et al., 2014). The approach has demonstrated significant potential in the development of flexible and robust adaptation plans under conditions of deep uncertainty (Ranger et al., 2013, Reeder and Ranger, 2011, Haasnoot et al., 2013).

This thesis adopts a pathways approach to adaptation planning as it: (i) facilitates the consideration of a range of plausible future states of the world; (ii) explicitly recognises the sequential nature of long-term planning processes; (iii) reinforces the value of maintaining flexibility; (iv) incorporates robustness into the planning process; and (v) can be used as the basis for the production of salient and actionable decision support tools (Reeder and Ranger, 2011, Walker et al., 2013). This thesis seeks to demonstrate how adaptation pathways can support urban adaptation decision-making within an overall framework for adaptation planning. In the case of London, there has been

limited consideration of long-term water supply, heat and surface water flood risks. An example of how a pathways approach may be utilised in response to each of these priority risks is demonstrated in this thesis.

Quantified risk appraisal is an appraisal method that can be used to identify and prioritise risk management actions that are proportionate to observed or projected levels of risk (IPCC, 2012, Beven and Hall, 2014). Probabilistic appraisal methods are increasingly being used to address drought and heat risks, alongside the appraisal of flood risk management, which is the natural hazard for which quantified risk analysis has seen the greatest application (Beven and Hall, 2014). This research aims to enhance the linkages between near and long-term risk management approaches by demonstrating how quantified risk assessment can be used to appraise the effectiveness of long-term adaptation pathways.

In addition to developing adaptation pathways in response to an individual risk, this thesis moves beyond the many calls for integrated urban adaptation research, and demonstrates how adaptation pathways may be developed in response to multiple climate risks. This research utilises an integrated assessment model to quantify the nature of the interdependencies between multiple climate risks and adaptation actions, and thereby capture a wider range of adaptation benefits.

Adaptation benefits will only be efficiently realised if adaptation planning and implementation are undertaken in a cyclical manner, and learning from previous planning cycles is used to inform future adaptation planning and decision-making. There is a growing emphasis on flexible adaptation planning approaches that can react effectively to change. This increases the need for ongoing monitoring of climate risk and the effectiveness of adaptation actions. To complement research on adaptation

pathways this thesis aims to critically explore how M&E fits within an iterative risk-based adaptation planning cycle.

Chapter 2 demonstrates a framework that links adaptation M&E, risk assessment and decision-making. The framework focuses on the role of adaptation M&E as a means of closing the adaptation policy cycle and embedding learning into future cycles of risk assessment and adaptation action. Adaptation in the Thames Estuary is used as a case study to explore the potential for linking adaptation risk assessment, M&E and decision-making.

Chapter 3 demonstrates how the development and appraisal of adaptation pathways in response to increasing water supply risk can inform adaptation planning. The approach links risk-based decision-making methods with the development of long-term adaptation pathways for London's urban water supply system. Chapter 4 demonstrates the application of an adaptation pathways approach to urban heat-risk management in London, highlighting the benefits of multiple heat-risk management pathways. Chapters 3 and 4 demonstrate the development and appraisal of adaptation pathways that respond to individual climate risks. These papers provide novel demonstrations of a pathways approach in an urban setting and contribute results relevant to decision makers in London. Chapter 5, however, brings together pathways research for London and uses this as a foundation for the development and appraisal of integrated pathways in response to multiple risks. The focus of Chapter 5 is the demonstration of how an integrated assessment framework is used to appraise city-scale adaptation pathways for London that respond to multiple climate risks.

2 **Closing the adaptation loop: demonstration of an integrated framework to link monitoring and evaluation with risk assessment and decision making**

2.1 INTRODUCTION

Adaptation monitoring and evaluation (M&E) processes have the potential to improve our understanding of climate change adaptation and increase its effectiveness by completing the adaptation planning cycle. Whilst methods for assessing climate risks are growing in maturity, considerable uncertainties remain in projecting the response of socio-ecological systems to climate change, with or without adaptation actions. We do not foresee these uncertainties being fully resolved, so adaptive learning loops are necessary.

Climate change adaptation may be incremental in response to proximate changes in risk or transformational in response to broader systemic change (Park et al., 2012, Pelling, 2011). Adaptation actions may include both physical and policy-based measures that reduce climate risk, alter drivers of social vulnerability, deliver adaptation benefits, or build adaptive capacity. Climate change adaptation, hereafter referred to as adaptation, is an ongoing process occurring in a diverse range of contexts and scales. To date, adaptation projects and programmes have mainly focussed upon marginal impacts in

selected sectors and proposed incremental responses. However as systemic impacts of climate change become increasingly likely complex system scale responses will be required (Park et al., 2012, Wise et al., 2014).

Monitoring and evaluation are complementary processes that use diverse tools to appraise the performance of interventions over time. Monitoring is the ongoing collection of information to measure progress against objectives, often focussing on indicators. Evaluation is a systematic examination of an intervention, often following implementation of a project, and it usually focuses on broader outcomes. In many instances, however, elements of M&E may be merged as part of an integrated process (Dinshaw et al., 2014). M&E is a well-established practice utilised in various sectors and contexts, including education, health and international development. Motivations for undertaking adaptation M&E vary depending on the context, including the desire to: evaluate the effectiveness of adaptation mechanisms (Ford et al., 2013, Lamhauge et al., 2013); learn about and improve the adaptation process (Villanueva, 2011); identify the impacts of adaptation actions on social vulnerability (Brooks et al., 2013); identify adaptation priorities (Ford et al., 2013, Lamhauge et al., 2013); justify adaptation expenditure (Ford et al., 2013, Lamhauge et al., 2013); understand how climate risk is changing (Hall and Borgomeo, 2013, ASC, 2012); inform decision-making processes (Villanueva, 2011); or, guide adaptive management (Hermans et al., 2014). Attributing causal links between adaptation actions and any outcome in the complex systems in which adaptation occurs is difficult (Pringle et al., 2012, Dinshaw et al., 2014, Mullan et al., 2013). Without a counterfactual, knowing to what extent an adaptation action contributed to avoiding a negative outcome becomes very difficult (Pringle et al., 2012, Dinshaw et al., 2014), reinforcing the need for adaptation M&E that values learning (Villanueva, 2011).

Although we do not yet know what the impacts of climate change will be and what the response of complex systems to a changing climate may be, both will directly affect future levels of climate risk. We argue that adaptation M&E has the greatest potential to contribute to better adaptation decision-making when it integrates M&E of actions and processes, as well monitoring climate risk and vulnerability.

During the extended periods relevant to adaptation multiple drivers are likely to change (in an uncertain manner), which means the effectiveness of an intervention may not be fully understood for long periods (possibly decades) (Pringle et al., 2012, Lamhauge et al., 2011, Dinshaw et al., 2014, Mullan et al., 2013). This reinforces the need for institutionalised adaptation M&E approaches that contribute to the required long-term data sets. Developing effective adaptation M&E processes will be vital in raising support for adaptation action; learning about the process of adaptation; and identifying successful approaches to improve the effectiveness of adaptation through time (Mullan et al., 2013).

Adaptation planning approaches that embrace flexibility and incorporate uncertainty into the decision-making process provide methods to develop robust adaptation outcomes within dynamic systems (Ranger et al., 2010a, Walker et al., 2013, Hallegatte, 2009). Such frameworks typically specify the need for monitoring decision triggers and iterative learning to occur, however limited progress has been made integrating the necessary M&E processes. Empirical evidence about the changing climate and nature of adaptation responses is required and this information and associated learning must be better integrated in future cycles of adaptation in an attempt to close the iterative adaptation-planning loop.

We present a *risk-based adaptation monitoring, evaluation, and decision-making framework* designed to complement decision centred iterative adaptation planning approaches. This framework is informed by a review of the adaptation M&E literature and approaches used in a range of contexts in which we identify unique features of adaptation M&E methods to better understand their strengths and weaknesses. Our proposed framework seeks to focus attention on the potential contribution of M&E to adaptation planning, demonstrating how it can contribute to informing risk assessment, adaptation decision-making and iterative learning. We use the Thames Estuary 2100 project (TE2100) as a case study to demonstrate how our framework can be applied in a real world setting. TE2100 is one of the UK's iconic adaptation projects: it developed a long-term plan for managing estuarine flood risk in the Thames Estuary and London, which is now being implemented (EA, 2012). We conclude with a discussion of the limitations of our framework and outlines ways forward.

2.2 ADAPTATION MONITORING & EVALUATION

In most iterative adaptation decision making cycles, the objectives are identified, followed by the development, implementation and monitoring and evaluation of a plan (Willows and Connell, 2003, Ranger et al., 2010a). Adaptation M&E can provide the necessary evidence to appraise the relative contribution of adaptation measures implemented to the agreed objectives (Villanueva, 2011, Ford et al., 2013). It can also capture learning that can assist in the development of objectives and strategy for future iterations, thereby closing the adaptation loop. This requires that M&E provides information that stakeholders to the decision making process consider credible, legitimate, actionable, and salient (Cash et al., 2003, Jones et al., 1999, IPCC, 2014).

This section briefly reviews a range of M&E approaches that may be used for adaptation M&E.

Result Based Management is a widely used ‘management strategy focusing on performance and achievement of outputs, outcomes and impacts’ (OECD, 2002). Large bilateral and multilateral development agencies, and initiatives such as the Pilot Program for Climate Resilience and the Adaptation Fund, have adopted and modified Result Based Management for adaptation M&E (Lamhauge et al., 2013). Outcome-based approaches share many similarities with Result Based Management, as both focus more on monitoring outputs and outcomes than understanding processes of change. Outcome-based approaches can help measure the effectiveness of adaptation in terms of reduced exposure or vulnerability to climate hazards (Ford et al., 2013, Harvey et al., 2011). Germany adopted an outcome-based approach at the national level to provide a national perspective on climate risk and preparedness, not to evaluate the effectiveness of specific adaptation actions (Schönthaler et al., 2010).

Theory of Change is an approach to programme design, monitoring and evaluation that has become increasingly influential in international development M&E (Bours et al., 2014). Theory of Change is recognised as a way to articulate how and why an intervention will lead to specific change (Stein and Valters, 2012). Theory of Change is central to the adaptation M&E approach outlined in ‘Tracking Adaptation and Measuring Development’ (Brooks et al., 2013); the guidance for M&E of climate change prepared by Bours et al. (2014); and the guidance document ‘Making Adaptation Count’ (Spearman and McGray, 2011).

Risk-based approaches to adaptation M&E include the monitoring of indicators of climate hazards, exposure, impacts, vulnerability, and adaptation to develop a multi-

factorial picture of climate risk. This allows for tracking of changing risk through time (Hall and Borgomeo, 2013, Sadoff, 2015). They have mostly been used at the national level including: Germany, Kenya, Morocco, Switzerland and the UK (Hammill et al., 2013).

Process-based approaches focus on tracking adaptation processes and the implementation of actions such as the development of an adaptation plan or the completion of a capacity building programme (Ford et al., 2013, Dinshaw et al., 2014). They are a pragmatic response to the difficulty in monitoring outcomes. They are suitable for monitoring adaptive capacity (IPCC, 2012, UKCIP, 2010, Pahl-Wostl, 2009), adaptation readiness (Ford et al., 2013) and adaptation preparedness (ASC, 2010, Heidrich et al., 2013). The mid-term and final evaluation of Finland's first national adaptation plan are examples of using a process-based approach at the national level to measure progress through a defined series of steps in an adaptation process (Finnish Ministry of Agriculture and Forestry, 2009).

In practice, adaptation M&E increasingly incorporates elements from multiple of the approaches discussed above (Hammill et al., 2013, Lamhauge, 2014, EEA, 2015). France, for example, combines annual monitoring of the implementation of adaptation interventions with mid-term and final evaluation of its national adaptation plan using a range of evaluation techniques, such as impact assessment, cost-effectiveness and cost-benefit analysis (Mullan et al., 2013). The UK's M&E framework allows policy makers to combine process, outcome and risk approaches using both qualitative and quantitative data (Hammill et al., 2013).

Nonetheless, given the scale of the adaptation challenge and nascent adaptation action, M&E is still embryonic. The underutilisation of M&E in decision-making is not limited

to adaptation, but the challenge is compounded by long timeframes, inherent uncertainty and difficulties with attribution (Dinshaw et al., 2014, Pringle et al., 2012, Mullan et al., 2013). To date, few examples exist of adaptation M&E contributing to adaptation planning and decision-making, making it difficult to effectively close the iterative loop that is included in most adaptation planning frameworks.

2.3 LINKING ADAPTATION MONITORING & EVALUATION, RISK ASSESSMENT, AND DECISION MAKING

A risk-based adaptation monitoring, evaluation and decision-making framework is proposed (Figure 2-1) that could contribute to overcoming coordination and information challenges by establishing a structure for institutional relationships and information flows. These three potentially complimentary processes, if effectively aligned, may improve adaptation outcomes and reduce long-term climate risk. Our framework includes three key processes: adaptation M&E, climate risk assessment, and adaptation decision-making processes.

These three potentially complimentary processes, if effectively aligned, may improve adaptation outcomes and reduce long-term climate risk by helping to ensure that: adaptation decision making is informed by credible information on climate risk and adaptation effectiveness; that climate risk assessments output salient and actionable information; and that efficiencies are realised by streamlining data capture for both M&E and risk assessment. We propose that information should flow on a cyclical basis, in the directions indicated by the linking arrows in Figure 2-1, to align and continuously improve these processes. By feeding the information from adaptation M&E into future climate risk assessment and decision-making, we seek to more effectively close the adaptation planning cycle and create an iterative planning loop.

The linkages and interactions between key processes of our framework are described next.

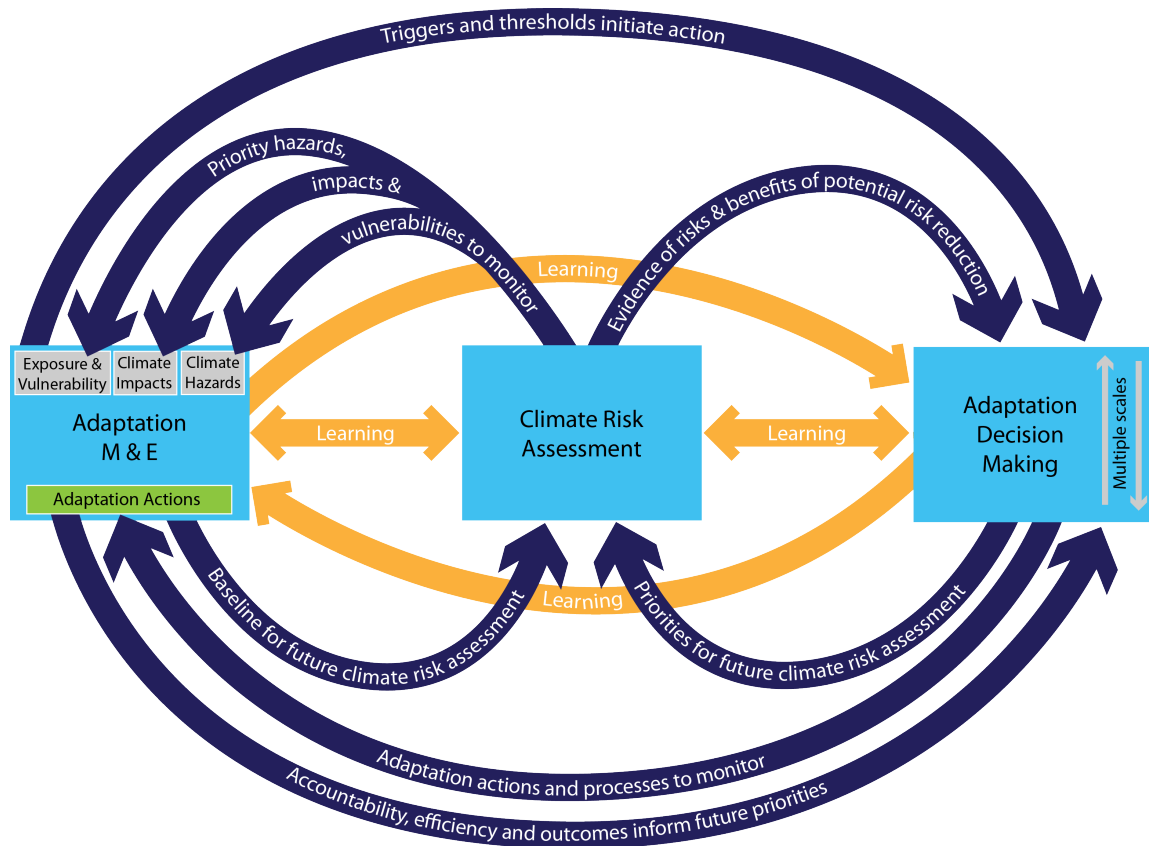


Figure 2-1 A risk-based adaptation, monitoring, evaluation and decision-making framework that outlines the interactions between key climate change adaptation processes

2.3.1 Climate risk assessment

Risk management approaches provide a method for managing uncertainty and integrating information from multiple disciplines (IPCC, 2012, IPCC, 2014). Climate risk assessment plays a central role in our framework to identify priority and emerging climate risks that should be managed through a process of adaptation, and the potential benefits of adaptation actions. It thus develops a critical evidence base that can inform adaptation decision-making (Hall et al., 2012b). Climate risk assessment identifies the climate hazards and impacts, communities, and assets for which exposure and vulnerability should be monitored.

2.3.2 *Adaptation M&E*

Monitoring should provide information on progress in implementing adaptation actions, and evaluation should seek to understand the effectiveness of actions as well as associated barriers and enabling factors. This framework further incorporates monitoring of climate driven changes in natural hazards, exposure, vulnerability, and climate impacts.

For M&E of adaptation actions the flexibility of approach is critical (EEA, 2015). Therefore, a combination of the most appropriate M&E methods and indicators should be selected based on the context and actors' priorities. Process-based approaches may prove valuable when the focus is building adaptive capacity, while Risk Based Management and outcome-based approaches are commonly used when focussing on effectiveness and efficiency of actions. Theory of Change provides a flexible approach in the face of inherent uncertainties, as it enables values, assumptions and priorities to be examined on an on-going basis, and adjustments to be made in response to specific triggers. Thus it can contribute significantly to learning and iterative decision-making.

Most adaptation M&E approaches utilise indicators (Hammill et al., 2013) but adaptation's complex nature means a combination of quantitative, qualitative and binary indicators may be required (Lamhauge et al., 2013). A portfolio of indicators can be used to provide evidence that a certain condition exists or certain results have or have not been achieved (Pringle, 2011). While indicators provide an overview of change, they cannot effectively explain how that change came about (Lamhauge et al., 2011). Indicator-based systems should therefore be combined with expert knowledge to interpret the results. An outcome indicator is typically chosen to demonstrate that a result has been achieved, whereas a process indicator is used to show that a process

designed to contribute to the achievement of an outcome has been completed (Ford et al., 2013).

Integrating the monitoring of adaptation actions and climate risks has challenges that include: allocating budget for monitoring; prioritising what can and should be monitored; determining the frequency of monitoring; and identifying who should undertake the monitoring, what should be done with the results, and by whom. Overcoming these challenges requires enhanced interdisciplinary collaboration between M&E specialists, adaptation practitioners, risk managers, climate scientists and local stakeholders. Resources for adaptation M&E should be proportionate to the resources invested in adaptation, levels of climate risk, and understanding of what contributes to successful adaptation.

An essential component of establishing effective long-term M&E is institutionalising review processes. Where climate risk is already monitored, information must be capitalised upon and made accessible, salient and relevant to decision makers, which will require partnership and effective dialogue. One approach is to exploit existing partnerships (such as the London Climate Change Partnership (LCCP): a collection of organisations that contribute to increasing London's climate change preparedness (LCCP, 2015)) that can work with members to establish a monitoring framework and the effective flow of information between partners.

2.3.3 Adaptation decision making

An adaptation decision-making process identifies and prioritises the type, extent and timing of adaptation actions. This may include the development of an adaptation plan, pathways or portfolios of action, and can occur at a range of spatial and administrative levels. The efficiency and reliability of adaptation actions are another important

consideration, which are initially determined from historic information from similar contexts. Learning about adaptation efficiency and long-term effectiveness through adaptation M&E informs future adaptation decisions. Adaptation actions are prioritised based on criteria appropriate to the decision context: for example where cost-benefit criteria are appropriate the benefits may be identified as marginal risk reduction. The decision-making process identifies adaptation actions to be implemented and thus monitored. Adaptation decision-making should inform and be informed by the adaptation M&E and risk assessment processes as part of the iterative framework.

The risk assessment process identifies stakeholders' tolerable risk thresholds, while triggers for additional adaptation actions may be identified as part of the decision-making process. Decision triggers may identify levels of vulnerability, impact, hazard or exposure, be combined in a risk-based metric or relate to adaptation actions. Portfolios of indicators with option dependent triggers will assist in informing future adaptation priorities. In complex systems, exceeding a single trigger value is unlikely to provide sufficient evidence to alter an adaptation strategy. The monitoring of multiple decision-relevant indicators, however, will allow decision makers to understand the evolving system and act in the next policy window.

2.3.4 Feedback for future assessment

Well-aligned M&E and risk assessment processes can help capitalise on synergies. Monitoring current levels of risk and identifying emerging climate and socio-economic trends provides critical baseline information for future climate risk assessments. The most compelling climate risk assessments are well grounded in understanding of current climate risk (ASC, 2015). Well-designed M&E provides the evidence to

identify priority hazards, sectors, assets or locations, which again links back to and informs future climate risk assessments.

In many contexts implementing these processes in a complimentary manner is challenging because various actors – who may have different motivations, legislative requirements and information needs – undertake each process separately. Implementing such a framework will require coordination and institutional support, however this could be achieved through new or existing partnerships, coordination units or inter-institutional agreements.

2.3.5 Competing linkages

The framework explicitly identifies critical linkages between adaptation M&E, climate risk assessment and adaptation decision-making that may exist in tension as separate processes. For example, learning about the implementation process and ensuring accountability throughout the delivery of outcomes are often competing motivations for adaptation M&E. Competing objectives can diminish the delivery of information required to enhance adaptation (Spearman and McGray, 2011).

Adaptation M&E can improve decision-making accountability by providing evidence of actions' effectiveness and efficiency. The long-term monitoring of climate risk can help to demonstrate the tangible benefits of adaptation in terms of reduced climate risk. Combining M&E of climate risk and adaptation action allows both the scale of the adaptation challenge and the response to be better understood. Demonstrating the need for adaptation can help secure necessary financing, whilst understanding which actions are effective can help target resources where they may deliver most value.

2.3.6 *Learning*

Given planned adaptation is a relatively new and ever evolving challenge, learning should be prioritised. Learning from a system's response to changing climate impacts and the implementation of adaptation is important, as this improves understanding of the context for future adaptation. Learning from the implementation of adaptation is important to understand what has contributed to successes or failures - i.e., what 'works' in practice. Evaluation is critical in revealing whose perspectives were considered when critical adaptation decisions were made and how adaptation problems were framed.

Evaluation of the adaptation M&E, risk assessment and decision-making processes is critical to improving each component of the planning cycle, but also to learning how to better align the processes and share findings. Qualitative approaches can ensure learning is captured, contextual information developed and multiple perspectives considered. Evaluation and learning approaches should be flexible and contribute to understanding unintended and unexpected outcomes.

2.4 ADAPTATION MONITORING & EVALUTATION, RISK ASSESSMENT AND DECISION MAKING FOR THE THAMES ESTUARY

This section demonstrates how our framework could be implemented in the context of managing long term tidal and fluvial flood risk in the Thames Estuary, UK. We use TE2100 as an example as it is a pioneering adaptation project that incorporates many of the key elements of risk assessment, adaptation M&E and decision-making in our framework. Furthermore, as the final plan was published three years ago and the

monitoring programme was scheduled to commence five years ago, it provides an opportunity to learn from the challenges of implementing adaptation M&E.

An initial review of project reports and stakeholder interviews were undertaken to understand how TE2100 incorporated adaptation M&E. Follow up interviews were completed to identify which stakeholders are responsible for monitoring which indicators, who uses the collected information and for what purpose. We compared TE2100's adaptation M&E approach with our framework to learn more about the barriers and enablers of adaptation M&E, as well as demonstrating how our framework could be applied in practice.

The Environment Agency (EA) has invested significantly in climate risk assessment and adaptation planning for the Thames Estuary. As part of this, the TE2100 Plan for long-term tidal flood risk management for London and the Thames Estuary was published in 2012 (EA, 2012). A critical component in the development of the TE2100 Plan was a risk assessment, which included identifying existing levels of vulnerability; collating and generating climate information; assessing the sensitivity of existing flood risk management approaches to future climate; identifying thresholds relevant to decision making (e.g. values for mean sea level (MSL) that trigger the need to modify existing flood defences); and identifying and appraising the effectiveness of potential adaptation actions (Ranger et al., 2013).

The development of the TE2100 Plan included appraising adaptation portfolios using multi-criteria assessment and prioritisation of preferred pathways (Ranger et al., 2013). The preferred pathway identified includes staged long-term modification of the Thames Barrier; and the management of fluvial and pluvial flooding through local measures

including making space for water, local flood defences, building resilience measures, flood forecasting and emergency planning (EA, 2012).

2.4.1 Indicators and triggers

The TE2100 project monitors ten indicators, which we would classify as indicators of climate hazard, exposure and vulnerability. The outputs from the monitoring programme will inform the scheduled review and re-appraisal of the TE2100 Plan every ten years. They will also inform the timing of future adaptation actions and trigger decision-making if rapid change occurs in one or more of the indicators (EA, 2012). Table 2-1 comprises the TE2100 adaptation indicators; methods for data collection; who contributes to monitoring (in addition to the Environment Agency TE2100 team); trigger values; and purpose of monitoring each indicator.

An interim evaluation and review of the ten TE2100 indicators is undertaken every five years. The first interim-review will be completed in 2016. Some of the TE2100 indicators have pre-defined trigger values, such as the number of closures of the Thames Barrier. In the winter of 2013/14 the threshold value of 50 barrier closures was exceeded (EA, 2014), which triggered a review of flood risk management in the estuary and an update on the Environment Agency's TE2100 monitoring programme was prepared. In the Environment Agency review, however, no evidence was identified to suggest that any of the relevant TE2100 indicators have approached or exceeded the levels that would trigger a change in plan (EA, 2014).

Table 2-1 TE2100 adaptation indicators

Indicator	Method of collection	Monitoring Partners	Trigger value	Purpose
MSL	Tide gauge measurements	Port of London Authority	-	MSL impacts the number of times per year that a barrier must be closed and the area of intertidal habitat. Change in MSL also provides an indication of how the peak surge tide level may change.
Peak surge tide level	Tide gauge measurements and sea level modelling	Port of London Authority	3.75m above ordnance datum at Southend	Flood forecasting and risk assessment. Peak surge tide level also determines the design crest level of flood defences.
Peak river flood flows	Based on updated estimates of extreme values	EA – flood forecasting unit	-	Flood forecasting and risk assessment in West London and where tributaries meet the estuary.
Condition of flood defence assets	Visual surveys and updated asset register	EA – asset performance teams and Thames Estuary Asset Management 2100 Programme (TEAM2100)	-	To inform the repair and renewal of defences in order to achieve the best value for money in investment programmes/future risk assessment
Frequency of closure and reliability of the Thames and other barriers	Maintenance of operational register & review of reliability assessments	EA - Thames Barrier operations and TEAM2100	50 closures per year	To ensure that the annual probability of failure of these structures does not exceed the required level.
Developed area or asset value of development	Not specified – under development	Greater London Authority and local planning authorities	-	Maintain a database of social and economic information for flood risk management planning.
Extent of erosion/deposition	Local visual surveys and estuary-wide geomorphology studies	EA – Local asset performance teams and TEAM2100	-	To identify the extent of defences threatened by erosion and to monitor the cumulative effects on the environment of flood defence structures.
Intertidal habitat area including mudflat and saltmarsh	Lidar surveys and aerial photography supplemented by on the ground surveys	EA – biodiversity and habitats team and the estuarine and coastal monitoring and assessment service	-	Maintain intertidal habitat zone and ensure compliance with European Union habitats regulations
Spatial planning and development activities	Under development	Local planning authorities	-	To measure how well flood risk adaptation actions are being factored into development.
Public/institutional attitudes to flood risk	EA national level survey	EA – national market research team	-	Public (hence political) appetite for risk, and institutional preparedness to manage risk and to plan for/respond to emergencies.

2.4.2 *Implementation of monitoring*

During the first review period, much of the practical work has focussed on exploring options for what could feasibly be monitored and how. Strong relationships with monitoring partners have helped to facilitate access to data. Successful monitoring has been easiest to facilitate where existing long-term data sets are utilised, such as for mean sea level and condition of flood defence infrastructure undertaken directly by the Environment Agency. For indicators that have not historically been monitored across the estuary, stakeholders have stated that establishing a baseline has been ‘practically impossible’. Challenges have emerged in monitoring indicators for: (i) building regulation as it is difficult and often costly to measure the amount of flood resilient development undertaken; (ii) local attitudes toward flood risk – a national level assessment is used but unique local conditions are likely to affect awareness of flood risk; and (iii) the impact of estuary geomorphology on flood defences, as monitoring is costly and the relevant geomorphological processes are not well understood. These indicators are also perceived by stakeholders implementing the monitoring programme to have a lower priority.

Stakeholder responses to consultation undertaken as part of the development of the TE2100 Plan indicated a need for greater support and increased clarity of the roles and responsibilities of implementation partners (EA, 2012). Similarly, there is a need for greater clarity as to how stakeholders may contribute to future M&E. Identifying people with appropriate experience and expertise to undertake the monitoring has been a key challenge, alongside securing funding for long-term monitoring.

The Environment Agency is actively pursuing strategies to overcome practical M&E challenges. They are seeking funding from other TE2100 stakeholders, some of which

may contribute to monitoring. A working group was established to facilitate the utilisation of research from national and international partners in monitoring mean sea level and peak surge level. The Environment Agency has also developed and strengthened relationships with academic partners so academic contributions may inform monitoring. Furthermore, we have observed the importance of individual champions within the Environment Agency in maintaining a commitment to adaptation M&E in the face of competing priorities. It remains unclear if commitments made in planning documents are sufficient to ensure monitoring is implemented. Initial challenges were identified in the first interim monitoring review that, if overcome, will see a more comprehensive monitoring system in place to inform the 2020 review.

2.4.3 Framework applied to TE2100

Despite the TE2100 Plan successfully integrating monitoring into long-term planning, we argue that it would benefit from a better-integrated approach that adopts a broader definition of adaptation M&E. As a demonstration we have incorporated existing elements of TE2100 into our framework and inserted proposed components as per Figure 2-2 and the discussion below. Whilst TE2100 includes a number of the elements in our framework, the relationships between processes and linkages have not been clearly articulated. Clearly identifying linkages between M&E, risk assessment and decision making will provide clarity to stakeholders, and contribute to delivering a compelling adaptation narrative to decision makers.

Adaptation M&E could be expanded to the monitoring of adaptation actions and climate impacts (complimentary indicators such as the costs and damages from extreme fluvial flooding and storm surge events). Better understanding progress in implementing adaptation actions and potential trends in climate impacts will increase

understanding of how climate risk varies over time. Process-based methods can be used to monitor the delivery of the policy-oriented adaptation actions (Ford et al., 2013, Dinshaw et al., 2014). Outcome-based approaches are well suited to monitoring the delivery of physical interventions – such as tracking the number of properties with property level flood defences. Outcome-based approaches are best suited to data rich contexts, such as the Thames Estuary, where they can contribute to systematically quantifying levels of climate risk and adaptation effectiveness (Ford et al., 2013).

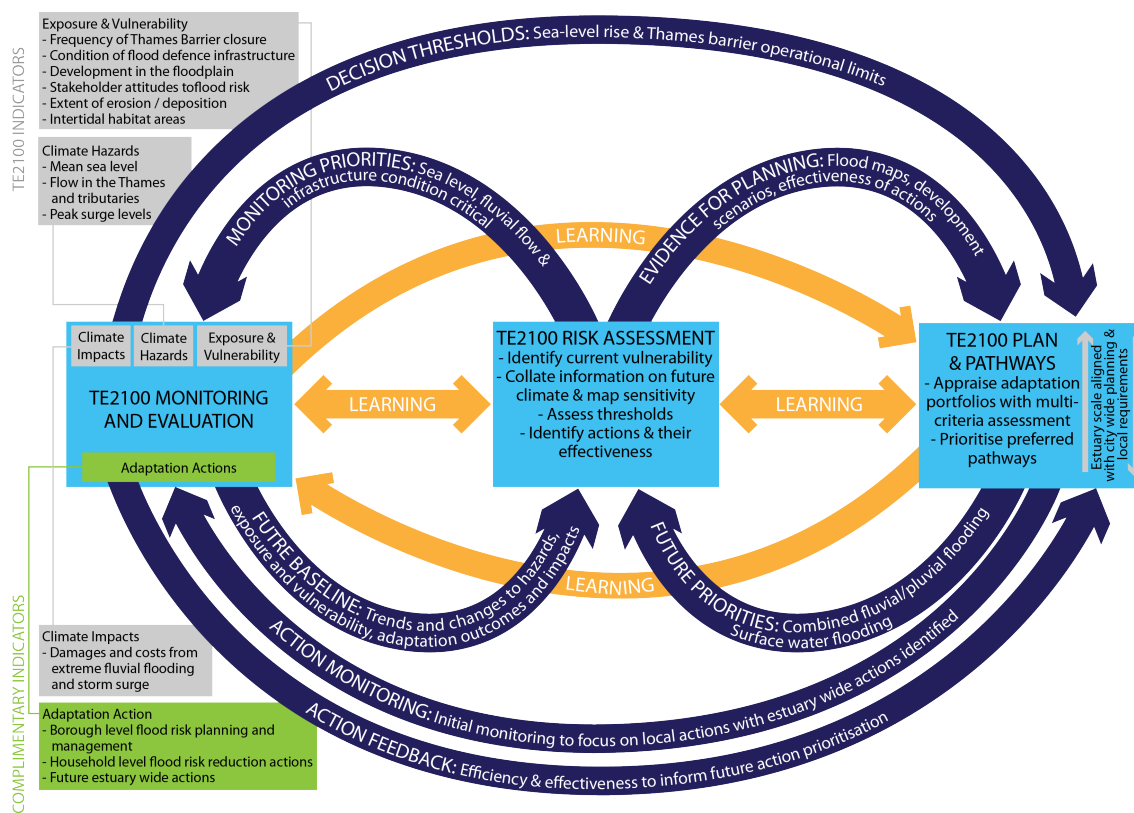


Figure 2-2 A risk-based adaptation, monitoring, evaluation and decision-making framework that outlines the interactions between climate change adaptation processes relevant to the TE2100 adaptation project

Further consideration beyond monitoring the stakeholder attitudes to risk should be given to the cultural, political and governance factors, as societal change will shape the context in which TE2100 will be implemented (Pelling, 2011). Theory of Change approaches could contribute to understanding the contextual factors that will influence

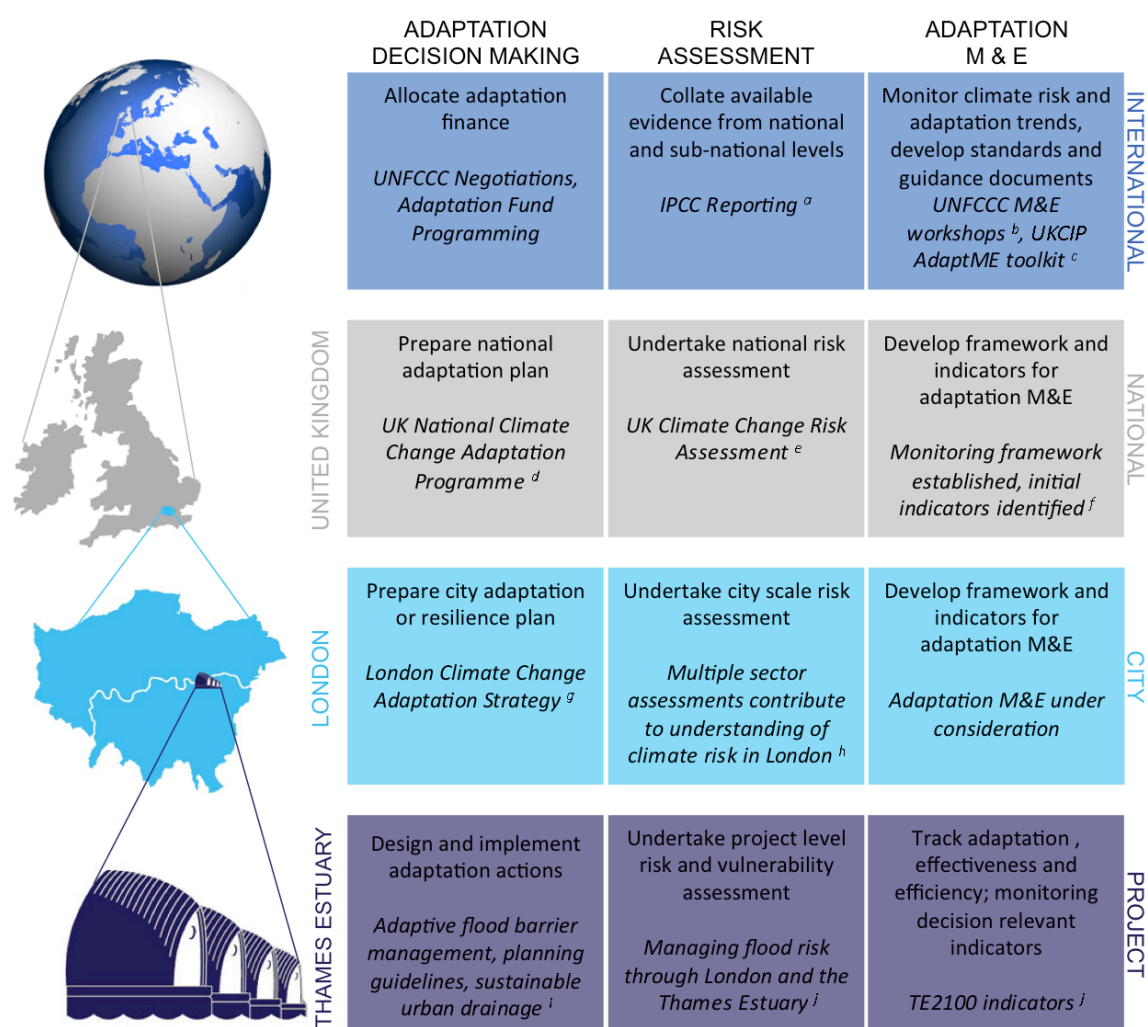
the long-term success of TE2100 and if necessary conditions exist to implement the adaptation actions in the TE2100 Plan (Bours et al., 2014).

Learning is a critical component of adaptation M&E and while multi-directional learning is not formally captured within the TE2100 we identified three pertinent examples. The innovative adaptation pathways approach pioneered in TE2100 means it is widely studied and similar methods adopted in numerous contexts (Ranger et al., 2013, Walker et al., 2013), which contributes to a knowledge base that is being drawn upon internationally. As the approach has now been used at various scales and in different contexts, learning about adaptation planning and decision-making should be captured to inform the next iteration of the TE2100 Plan in 2020. Lessons were identified in the review following the 50 barrier closures in 2013/14, particularly with regards to the interaction between fluvial and tidal flooding during high flow conditions, which may inform future baselines. The review also identified the need for monitoring reports to be prepared in a consistent manner that meets the needs of all stakeholders (EA, 2014). Decision makers should implement this learning about the effective use of adaptation M&E across the M&E programme.

2.4.4 Adaptation at multiple scales

Adaptation decision-making, climate risk assessment and adaptation M&E are undertaken at multiple administrative levels, each with distinct challenges. Of which, a key adaptation M&E challenge is how stakeholders can work effectively across governance levels. Figure 2-3 shows the TE2100 (large-project) in context with London (city), the UK (national) and international scales with examples of adaptation M&E, risk assessment and decision-making activities undertaken.

The Greater London Authority (GLA) utilises information collected at lower and higher governance levels, highlighting cross-level challenges in implementing adaptation M&E. For the Greater London Authority it is important to ensure the accountability of its adaptation programme, but it is equally as important to develop an understanding of overall trends (in risk and adaptation), capture learning about what has contributed to success, and identify gaps and challenges to inform the future adaptation strategies.



a (IPCC, 2014) b (UNFCCC, 2013) c (Pringle, 2011) d (HM Government, 2013) e (HM Government, 2012) f (ASC, 2012, ASC, 2015) g (Nickson et al., 2011) h (LCCP, 2012b) i (EA, 2012) j (EA, 2009)

Figure 2-3 Adaptation decision-making, risk assessment and M&E examples drawing examples from the global to project governance levels

Identifying and accessing the necessary data to monitor meaningful adaptation indicators remains difficult for the Greater London Authority. They have identified that working with borough governments (local level) and the Adaptation Sub-Committee of the Committee on Climate Change (ASC) (national level) would be advantageous, given their shared objectives (especially to utilise information related to spatial planning and flooding: areas where local authorities have statutory responsibility), and avoid replicating monitoring undertaken by the Adaptation Sub-Committee (for the sake of efficiency). Translating nationally relevant indicators to the city level would require additional resources to disaggregate national datasets not designed with sub-national uses in mind. Budget constraints, competing priorities, capacity constraints, and the lack of a statutory requirement are barriers to long-term adaptation planning amongst UK local authorities (ASC, 2015, Porter et al., 2015). These constraints also limit local authorities' ability to undertake adaptation M&E and feedback information to the Greater London Authority.

The Greater London Authority identified that assigning and maintaining responsibility for a shared risk is challenging, as many urban adaptation measures do not have a defined 'owner'. A flexible decision-oriented framework that can be utilised at multiple scales provides a structure to develop complementary approaches across levels. Whilst an idealised scenario, we argue it presents potential benefits in maximising efficiencies and the long-term effectiveness of adaptation. Key potential enabling factors that stakeholders from the Greater London Authority, Adaptation Sub-Committee, London Climate Change Partnership and Environment Agency identified included: developing shared adaptation M&E objectives; creating partnerships; institutionalising adaptation M&E; establishing statutory requirements (where sufficient political will exists); and

ensuring that sufficient financial and technical resources are dedicated to long-term M&E.

2.5 CONCLUSIONS

A need exists to grapple more critically with how M&E fits within an iterative adaptation planning cycle. This requires further consideration of the purpose of adaptation M&E, how it can inform decision-making and ultimately improve adaptation outcomes. As a contribution to this, we propose and demonstrate a framework that links M&E, risk assessment and decision-making, with a focus on the role of adaptation M&E. This is intended as a means of closing the adaptation policy cycle and embedding learning in future cycles of adaptation.

The growing emphasis within adaptation planning approaches on reacting flexibly to change increases the need to better understand changing climate risk, the context for adaptation decision-making and the effectiveness of adaptation actions. Indeed the dynamic interaction between changing climate risk, the socio-political decision-making context and system response is possibly the most severe source of uncertainty in these decision-making frameworks. Applying our framework to TE2100 highlights the value of monitoring climate risk indicators to inform decision triggers, and also monitoring the effect of subsequent action on risk for future assessment and decision-making.

Demonstrating the effect of adaptation actions is critical to ensure resources are spent effectively and to make the case for further investment. The limited resources available for adaptation in many contexts – including London and local authorities across the UK – further make adaptation M&E a critical process to inform how adaptation resources can be utilised best. As more adaptation planning initiatives complete their first

iterative cycle, demand to know if adaptation is managing long-term risk in an efficient and effective manner, or if adaptation triggers are being approached, will increase.

Many of the planning initiatives implemented to date, including TE2100, are examples of incremental adaptation in relatively closed systems (Wise et al., 2014). Our framework was demonstrated to inform incremental adaptation, however the nature and potential value of adaptation M&E to inform transformational adaptation still requires further exploration. As Wise et al. (2014) argue, in complex socio-ecological systems, where no clearly identified decision-maker exists and incremental adaptation may be insufficient, monitoring and understanding current vulnerability and drivers of risk are key challenges that need to be further considered.

There remains relatively few cases in which adaptation has moved to full scale implementation and even fewer examples of adaptation M&E being implemented. Learning from successful adaptation M&E can be difficult due to the long-term nature of adaptation, and further empirical examples need to be reviewed as initial phases of adaptation M&E are completed. Our review of TE2100 demonstrated that learning has already occurred through improved understanding of pathways methods, the nature of interrelated risks, and the importance of effective stakeholder communication. What remains to be demonstrated is how this learning can be capitalised upon.

We suggest that opportunities exist to utilise the proposed framework in other contexts to design locally relevant approaches for M&E, risk assessment and decision-making that will contribute to closing the adaptation-planning loop in a manner that balances competing adaptation M&E priorities. Barriers remain, however, in terms of implementing an integrated approach that requires participation from multiple stakeholders across governance levels.

Critical thinking and creativity are required in the design of M&E to ensure it does not become a formulaic process. During implementation a focus on participation and engagement will strengthen linkages, helping to ensure credible and actionable information is produced that contributes to decision-making and improved adaptation outcomes (Cash et al., 2003, Jones et al., 1999, IPCC, 2014).

3

Adaptation pathways in practice: mapping options and trade-offs for London's water resources

3.1 INTRODUCTION

The prosperity of cities worldwide requires reliable water supply systems. A high degree of uncertainty exists however, as to how drivers such as population growth and climate change will affect the reliability of water supply in the future. Climate change adaptation is an ongoing process of risk assessment, action, re-assessment, and response (IPCC, 2012). Water resource management decisions on how and when to invest in infrastructure or demand management are being made now that will affect the long-term resilience of water supply systems (Hallegatte, 2009, Hall et al., 2012d). Such decisions will contribute to enhanced water security, flexibility and robustness; or adversely, reduced resilience, mal-adaptation and undesirable lock-in (Ranger et al., 2010a). Their importance makes overcoming the barriers to adaptation faced by resource managers crucial (Hallegatte, 2009, Barnett et al., 2015).

Successful adaptation will require combinations of adaptation actions to be implemented through time in complex systems. Adaptation decision support needs to consider the timing, rate and scale of implementation of multiple actions distributed throughout a system as part of dynamic adaptive portfolios. Dynamic adaptive plans

have been proposed as an effective mechanism for managing issues characterised by deep uncertainty (Walker et al., 2013). A range of approaches for developing adaptive plans have been proposed; however, the uptake of such methods has been relatively limited compared to the scale of adaptation that is required around the world (Walker et al., 2013, Nakhooda et al., 2013). This may be because of the perceived complexity of such formal decision analysis methods, or because of a proliferation of alternative approaches. Institutional path dependency and capacity constraints are barriers to adaptation, and they restrict how readily practitioners may incorporate a long-term adaptation perspective into decision-making processes that are already explicitly (e.g., flood risk management) or implicitly risk-based (e.g. water resources planning).

A clearly defined yet flexible approach to adaptation can provide structure to guide the decision-making process. A range of frameworks have been developed, many building on the pioneering adaptation approach of Willows and Connell (2003), each with unique strengths. ‘Bottom-up’, vulnerability-based approaches have been found to be well suited to addressing an existing adaptation deficit, when planning horizons are short and climate and non-climate risks are inter-related (IPCC, 2012, Brown et al., 2012, Nazemi et al., 2013). Policy-first approaches are effective in incorporating stakeholder input (Ranger et al., 2010a). Risk-based approaches are suited to the management of well-characterised uncertainties (Hall et al., 2012a). Robustness based approaches can be difficult to apply in the development of dynamic long-term plans (Walker et al., 2013), but it is important that any approach considers the robustness of near-term decisions that have long-term implications given the deep uncertainties surrounding future climate and socioeconomic change (Hallegatte, 2009, Wilby and Dessai, 2010, Ben-Haim, 2006, Hall et al., 2012c, Lempert and Schlesinger, 2000).

Adaptation pathways are a policy-first approach to decision-making that targets analysis at the adaptation challenge (Ranger et al., 2010a). A pathways approach that sequences the implementation of actions over time to ensure the system adapts to the changing social, environmental and economic conditions will build flexibility into the overall adaptation strategy (Ranger et al., 2010a, Haasnoot et al., 2012). An adaptation pathway provides a visual representation of the potential sequencing and type of actions that may be implemented in the future. Monitoring of decision-relevant variables is an important component of implementing a pathways approach (Yohe and Leichenko, 2010) as it establishes a link between risk assessment and action that many adaptation approaches lack.

Risk and vulnerability assessments are increasingly recognised as complimentary processes. Adaptation frameworks, such as the one developed by Wilby and Dessai (2010), that combine top-down and bottom-up assessments can leverage the advantages of both (IPCC, 2012, IPCC, 2014). Pathways approaches should explicitly recognise and respond to existing management practices, which decision makers are familiar with and may have a legislative requirement to fulfil (Brown et al., 2011a), to more fully capture the benefits of considering near and long-term planning horizons.

A pathways approach was first applied as part of the Thames Estuary tidal flood risk management project in London (Ranger et al., 2010a). Adaptation pathways allow for a broad framing of the adaptation decision problem and have subsequently been used in a range of contexts (Haasnoot et al., 2012, Siebentritt et al., 2014, Barnett et al., 2014, Rosenzweig and Solecki, 2014, Lawrence et al., 2013, Wise et al., 2014, Haasnoot et al., 2013). Pathways approaches show significant potential for contributing to long-term adaptation planning (Haasnoot et al., 2012, Barnett et al., 2014, Park et al., 2012,

Rosenzweig and Solecki, 2014, Wise et al., 2014, Lawrence et al., 2013); however, pathways have not been applied to long-term planning of urban water supply systems to date, which restricts their potential for uptake in such contexts. There is a need to continue developing, trialling, critiquing and demonstrating how pathways approaches can respond to barriers and be utilised in informing and motivating adaptation planning in different contexts (Wise et al., 2014, Haasnoot et al., 2012, Barnett et al., 2015).

To address this need, this paper introduces a framework for adaptation planning in urban water supply systems under transient population and climate scenarios. The framework links existing risk-based decision-making, adopting the risk based appraisal framework proposed by Hall and Borgomeo (2013) and first demonstrated by Borgomeo et al. (2014), with the development of long-term adaptation pathways. However, it goes beyond the work described in these papers by linking, for the first time, quantified risk analysis with consideration of adaptation pathways. We illustrate how adaptation pathways can be used to inform urban water resources adaptation planning by developing long-term pathways for London's water resources. We present a quantified assessment of how risk of water shortages in London is projected to vary dynamically depending on the choice of adaptation pathway and under different transient climate and population scenarios. This approach has helped to reconcile multiple decision timescales and demonstrate the value of strategic long-term adaptation planning to stakeholders by outlining long-term futures that may influence medium-term decision-making.

Demonstrating our proposed framework with a case study is critical to advancing adaptation theory and practice, as climate change adaptation cannot be separated from the context in which it is occurring (Rosenzweig and Solecki, 2014). In the next section

we provide an overview of London's water resources, before outlining our pathways methodology and its alignment with existing decision making in Section 3.3. Section 3.4 describes the application of our methodology to our case study, including the development of a range of plausible pathways for London's long-term water supply to 2100. Section 0 presents an adaptation pathway diagram and results from the appraisal of the pathways in managing long-term water supply risk. Finally, the process of developing adaptation pathways and the results are discussed in Section 3.6.

3.2 LONDON'S WATER RESOURCES

London's water supplies are being stretched by increasing population and reducing water availability (EA, 2013). London's drinking water demands are primarily supplied by surface water abstraction from the Rivers Thames and Lee and, to a lesser extent (approximately 20%), groundwater sources. Furthermore, a 150 Ml/day desalination plant and reserve aquifers can be activated to supply water to London during times of drought. Water supply in London is managed by four private water companies, and regulated by the Environment Agency and the water supply regulation authority. This study focuses on the London Water Resource Zone (LWRZ), which includes 85% of London's residents. The LWRZ was chosen as it has been extensively studied, data for quantitative analysis is available, and the technical and institutional challenges being faced are representative of those being addressed across London. London has been classified as a water-stressed city and already faces water scarcity challenges (EA, 2013). In March 2012, water restrictions came into force across London as two consecutive dry winters caused very low levels in the River Thames and exceptionally low groundwater (GLA, 2012b). The water restrictions were lifted in April, when exceptional rains terminated the prolonged drought (Parry et al., 2013).

Climate change projections for the area suggest that by 2040 summer river flows and annual rainfall may decrease whilst temperature may increase (Murphy et al., 2009, Diaz-Nieto and Wilby, 2005). Overall water demand is expected to rise due to population growth and increasing single household occupancy (HM Government, 2012). Significant investment in water resource management is anticipated this century to maintain the existing levels of supply reliability and account for population growth and climate change (LCCP, 2012b).

Every five years water companies in London prepare asset and water resource management plans (WRMPs) that consider climate change, with a 25-year planning horizon. Supply and demand side actions are identified through detailed feasibility studies and investments are then prioritised taking into account financial, social and environmental costs (EA et al., 2012).

A range of regulatory and methodological barriers have restricted the extent that climate change adaptation has been considered in water resource planning in London to date. Current water management practices are not well suited for adaptation planning because of the short time horizon considered (25 years), the deterministic approach used to account for climate uncertainty and the inability to consider transient climate conditions (Hall et al., 2012d).

3.3 METHODOLOGY

Stakeholder consultations informed the development of our adaptation pathways and framework for integrating risk assessment and adaptation planning. Our framework (Figure 3-1) is risk-based and iterative, prioritises management of existing risks, and guides the development of long-term adaptation pathways. We consider adaptation

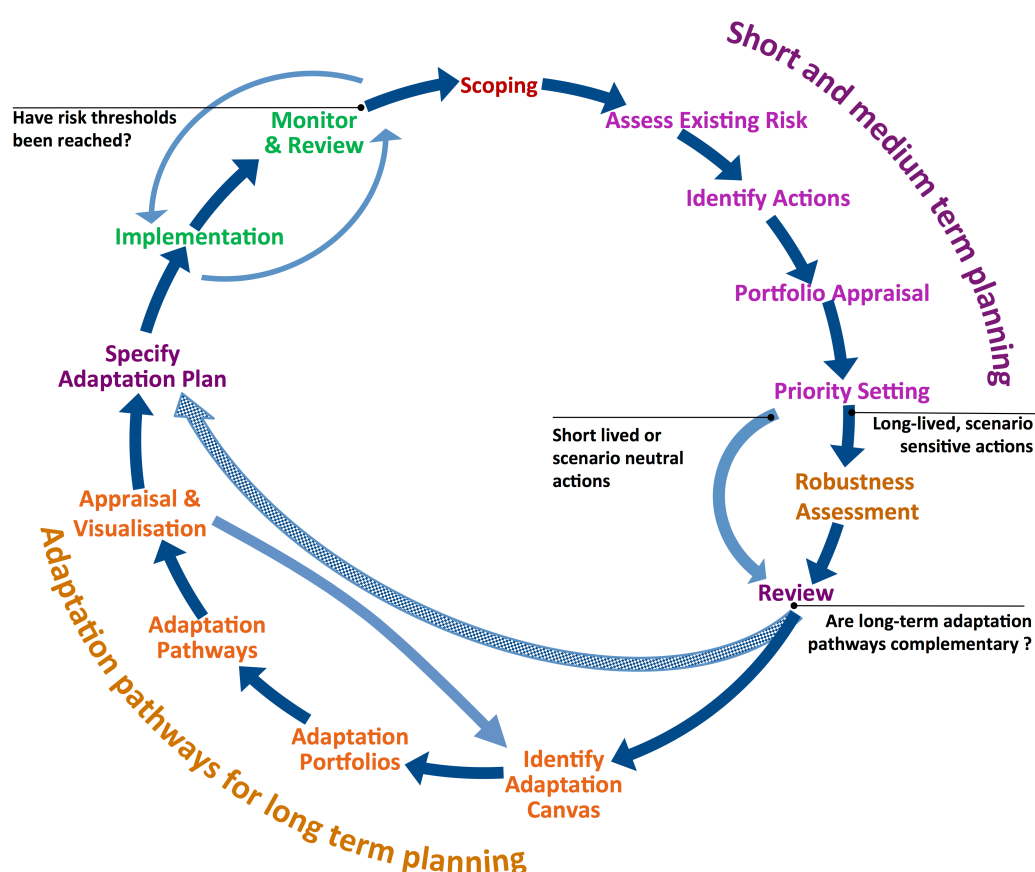


Figure 3-1 Integrated framework for adaptation planning that outlines the relationship between short and long term planning processes and the potential for adaptation pathways to complement short term planning

Semi-structured interviews were first conducted with key informants from the Greater London Authority (GLA), Environment Agency (EA) and Thames Water (TW) to identify near and long-term priorities for their organisations, ways in which they may

or may not be affected by climate change, and perceived barriers and enablers in adapting to climate change. The open framework of semi-structured interviews allowed for focused, conversational, two-way communication with small groups. One-on-one interviews, including ad-hoc conversations, and workshops with practitioners were conducted to better understand the potential role for additional decision-making support. Multiple meetings of the London Climate Change Partnership – a collection of organisations that contribute to increasing London’s climate change preparedness – were attended in 2013 and 2014 to further understand the context for adaptation planning in London.

Within our framework, the key methodological steps in the development of adaptation pathways include: (i) a review of the potential usefulness of adaptation pathways; (ii) identification of an adaptation canvas; (iii) selection of adaptation portfolios; (iv) development of adaptation pathways; and (v) appraisal and visualisation of adaptation pathways. This section outlines these steps.

3.3.1 Review

A review of existing risk management, governance and planning approaches helps in: understanding the extent to which climate change is currently being considered; identifying relevant planning horizons; establishing decision criteria and risk thresholds; and understanding stakeholder perspectives on the potential value in developing long-term pathways.

3.3.2 Adaptation canvas

Developing an adaptation canvas provides an opportunity to collate and consider a wide range of adaptation actions, their potential limits, and associated uncertainties. An adaptation canvas is a visual tool that illustrates the range of potential adaptation

actions and timeframes over which they are relevant, in this case potential supply-side and demand-side water resource options. Individual actions may be constrained by physical considerations: i.e. more water than exists in a river cannot be extracted from that river, nor more water re-used than that which reaches a wastewater treatment plant. Social and environmental considerations may also limit individual actions, given the recreational, navigational and biodiversity value of environmental flows. At some point, the economic cost of implementing further action will outweigh the risk reduction benefits. These limits will likely change through time in line with societies' values. This process helps to define a potential solution space and establishes the foundations for critical conversations about long-term decision making with a focus on adaptation actions.

3.3.3 Adaptation portfolios

Adopting a portfolio approach provides the flexibility to cope with a variety of possible future conditions and can help to compensate for the inevitable weaknesses or vulnerabilities of any particular action. Portfolios are drawn from the adaptation canvas and selected through working group consultations with stakeholders with the objective of identifying portfolios that are of interest to stakeholders, as well as spanning a broad range of potential futures.

3.3.4 Adaptation pathways

Pathways represent specific scenarios regarding the timing, rate and scale of implementation of multiple distributed and large discrete actions within the adaptation canvas. Actions in the portfolios are scheduled in consultation with stakeholders, also during working groups, to establish a range of potentially feasible timescales (including lead-time) over which adaptation options could be implemented at scale. Stakeholder

engagement enables stakeholders' perspectives and a broad range of pathways to be utilised in combination with probabilistic appraisal.

3.3.5 Appraisal and visualisation

Appraisal of sequential adaptation pathways demonstrates to decision-makers how climate risk may (or may not) be managed. A water resource system model is used to appraise the effectiveness of adaptation pathways in managing water supply risk and to calculate the present value cost of implementing each pathway. A risk-based indicator enables the costs of each action to be compared to the benefits in terms of risk reduction, which cannot be done as effectively with deterministic approaches often used by water utilities for planning purposes (Hall and Borgomeo, 2013). The risk-based metric integrates the impact of multiple drivers of changing risk including stream flow, population, per capita demand and adaptation action.

Building consensus on the need for change and how to best implement it is difficult (Barnett et al., 2014). Experience on the Thames Estuary 2100 project highlighted that an easily explainable pathways diagram was a valuable tool for facilitating conversations about managing long-term risk and developing an adaptive plan. Pathways diagrams that map potential pathways and identify trade-offs between adaptation action and climate risk are a key element of this approach. A pathways diagram brings together four attributes that change through time: (1) an indicator of the changing climate hazard; (2) an exposure indicator; (3) a dynamic adaptation pathway; and (4) a quantified indicator of climate risk. The time dimension provides a sense of the temporal scale at which a pathway is applicable, which assists decision makers in visualising the dynamic risk. During the implementation phase of an adaptive planning

cycle, the specification of adaptation actions should be informed by monitoring climate risk to ensure tolerable thresholds or triggers for action are not exceeded.

3.4 ADAPTATION PATHWAYS FOR LONDON'S WATER RESOURCES

This study demonstrates a pathways approach and its potential for informing the management of London's scarce water resources to 2100. Stakeholder consultations contributed to the co-development of a range of policy-relevant adaptation pathways. Our pathways approach was presented to a LWRZ working group on adaptation during which a series of adaptation portfolios were presented and discussed. Six portfolios were agreed upon as being illustrative of an interesting combination of future scenarios for London, as well as spanning a broad potential range of futures.

In a subsequent meeting, the full range of pathways presented in this paper and initial results were shared with the LWRZ working group on adaptation. A follow up focus group with technical specialists from TW and the EA was held to better understand the potential for this approach to align with existing analytical techniques and potentially contribute to decision-making. This section describes the application of our pathways method to the LWRZ and results.

3.4.1 Review

TW, the GLA and the EA are key stakeholders in determining priorities for long-term water resource management in London. These stakeholders have a strategic interest in the long-term management of the LWRZ. Existing levels of water supply risk are well managed in the LWRZ, but methods could be improved to overcome the limitations of a deterministic approach to dealing with uncertainty (Hall and Borgomeo, 2013).

All three stakeholders identified managing the long-term risk of water shortages in London, beyond the existing 25-year planning horizon, as a strategic priority. They agreed on the need to address the challenges of adapting to long-term change under conditions of deep uncertainty and expressed an interest in understanding the potential for adaptation pathways to be used in adaptation planning for water resources in London.

3.4.2 *Adaptation canvas*

We drew upon supply and demand side actions from the *Feasible Options List* developed as part of TW's Water Resource Management Plan (2015–2040) (Thames Water, 2014), which was developed in accordance with national water resource management planning guidelines (EA et al., 2012). These actions were identified as feasible options for deployment within the medium-term planning period (Thames Water, 2014). It was not within the scope of this research to independently identify water resource management actions for the LWRZ. The GLA prioritised demand management, including measures to reduce long-term per-capita demand from 170 to 110 litres per person per day (L/p/d), due to environmental flow considerations and potential savings for low-income households when combined with an effective social tariff (GLA, 2011c, GLA, 2012b).

We defined an adaptation limit as a point at which an action is no longer likely to be able to provide cost effective risk reduction, subject to social and environmental considerations. For example, individuals in households with the most water efficient fixtures and appliances currently available use 30 l/p/d less than the current average per-capita demand (GLA, 2011c). Stakeholders agreed that further reductions beyond this are unlikely, and as such 30 L/p/d was chosen as the adaptation limit; however,

given the high degree of uncertainty around demand reductions, this is an area for active monitoring.

During the Adaptation Canvas Step of the Adaptation Planning Framework, an adaptation canvas was developed to provide a visual representation of potential adaptation actions. During the subsequent Adaptation Portfolio and Adaptation Pathways Steps scenarios representing the timing, rate and scale of actions were developed. These were then overlaid on the Adaptation Canvas.

Figure 3-2 shows the adaptation canvas developed for the LWRZ includes 10 adaptation actions. Each pathway is overlaid as a line that represents the estimated yield that may be delivered by that action for the specified implementation scenario. The areas below the lines representing pathway 5² are highlighted for illustrative purposes. As demonstrated in Figure 3-2, pathway 5 includes a combination of demand and leakage reduction and a re-use scheme that would be operational in 2050. The actions for pathways 1-4 and 6 are included but not highlighted. Solid lines represent the period over which an action will be implemented, whilst dashed lines represent the period over which an action will continue to deliver a benefit in terms of reduced demand or increased supply. The estimated limits of each action were illustrated in the canvas as a potential contribution to the overall supply demand balance.

Each pathway highlights a scenario of interest to stakeholders. Each pathway is a scenario used to inform a planning process, as opposed to being a proposed plan.

² The pathways 1–12 described in this chapter, are pathways in response to water supply risk and refer to those described in Table 3-1. Pathways 1–12 in Chapter 4, refer to the series of pathways responding to heat risk as described in Table 4-3

Stakeholders' knowledge of the system, existing water availability and potential changes due to climate change and the desire to maintain water security informed pathway identification. Water availability was explicitly considered when appraising the pathways.

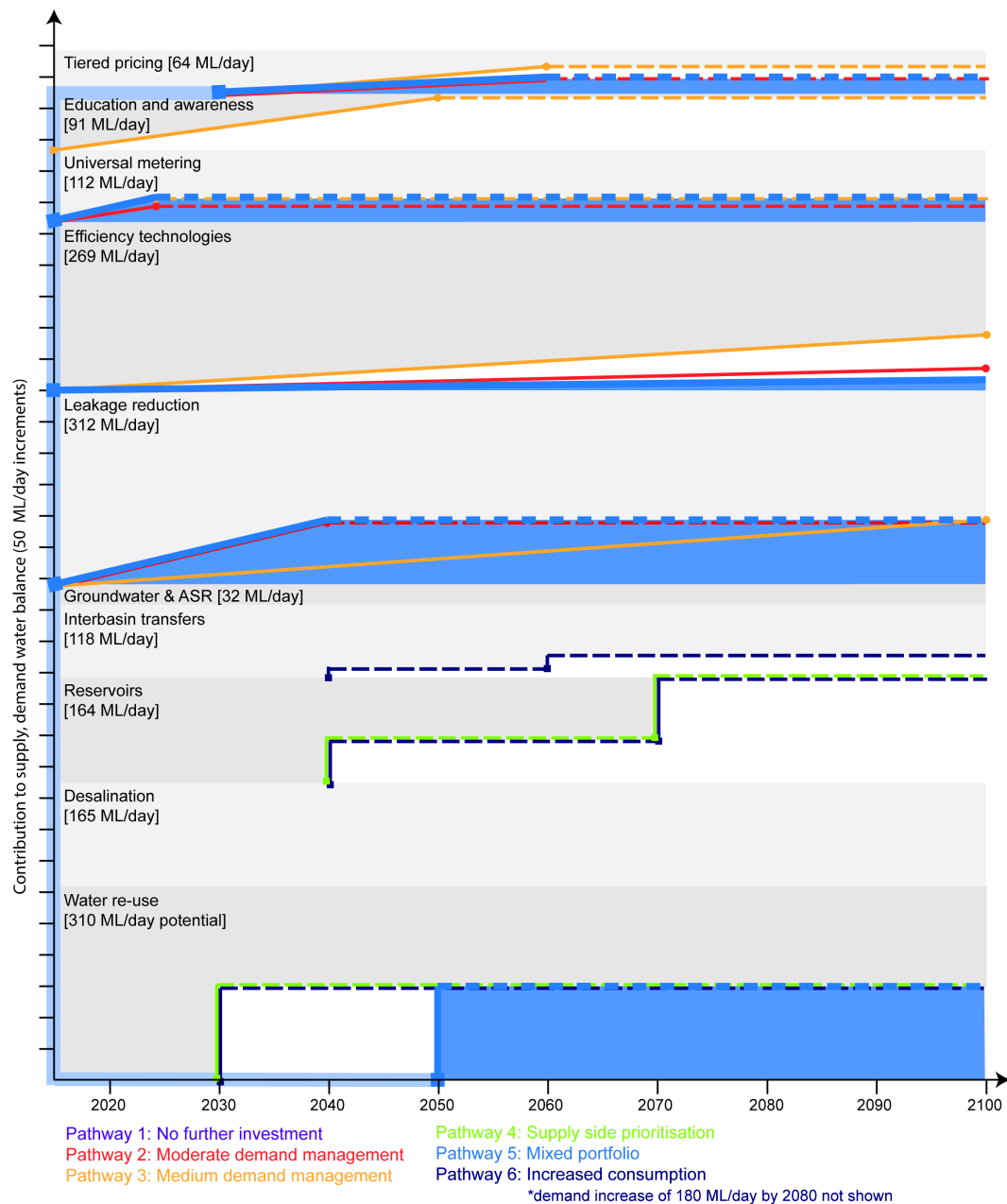


Figure 3-2 Adaptation canvas for London's water resources, highlighting Adaptation Pathway 5 - Mixed Portfolio High Population Growth. The adaptation canvas includes 10 adaptation actions. Each pathway is overlaid as a line that represents the estimated yield that may be delivered by that action for the specified implementation scenario.

3.5 ADAPTATION PORTFOLIOS

Six portfolios of actions were identified in consultation with stakeholders from TW, the GLA and EA:

1. **No further investment** – a do nothing scenario to provide a lower bound for adaptation action.
2. **Moderate demand management** – per-capita demand reduced by 10 L/p/d and leakage reduced by 104ML/d (20%) by 2100.
3. **Medium demand management** – per-capita demand reduced by 30 L/p/d and leakage reduced by 104ML/d (20%) by 2100.
4. **Supply side prioritisation** – existing demand maintained, and investment in re-use and two additional reservoirs.
5. **Mixed portfolio** – per-capita demand reduced by 10 L/p/d, leakage reduced by 104ML/d (20%) by 2100, and investment in an additional re-use plant.
6. **Increased consumption and abstraction** – per-capita consumption increased by 20 L/p/d by 2100, no leakage reduction, and investment in re-use, two reservoirs and inter-basin transfers.

These portfolios were intended as informative scenarios for long-term decision-making.

Further details of these portfolios are included in Table 3-1.

Table 3-1 Components of adaptation pathways 1–12

Pathway 1	Pathway 2	Pathway 3	Pathway 4	Pathway 5	Pathway 6
High Population Growth	High Population Growth	High Population Growth	High Population Growth	High Population Growth	High Population Growth
No further investment (existing per-capita consumption and leakage levels retained - 160 L/p/d & leakage 526 ML/day in 2100, utilise existing desalination (150ML/day))	Moderate demand management (per-capita demand reduced to 150 L/p/d, leakage reduced to 422 ML/day by 2100, utilise existing desalination (150ML/day))	Medium demand management (per-capita demand reduced to 130 L/p/d, leakage reduced to 422 ML/day by 2100, utilise existing desalination (150ML/day))	Supply side prioritisation (no demand side management, utilise existing desalination (150ML/day), re-use (150ML/day in 2030), new reservoir (63ML/day 2040 + 102ML/day in 2070))	Mixed portfolio (per-capita demand reduced to 150 L/p/d, leakage reduced to 422 ML/day by 2040, utilise existing desalination (150ML/day), re-use (150ML/day in 2050))	Increased consumption (per-capita demand increased to 180 L/p/d by 2080, utilise existing desalination (150ML/day), re-use (150ML/day in 2030) net increase in imports (29ML/day), new reservoir (63ML/day 2050 + 102ML/day in 2070).
Pathway 7	Pathway 8	Pathway 9	Pathway 10	Pathway 11	Pathway 12
Baseline Population Growth	Baseline Population Growth	Baseline Population Growth	Baseline Population Growth	Baseline Population Growth	Baseline Population Growth
No further investment (existing per-capita consumption and leakage levels retained - 160 L/p/d & leakage 526 ML/day in 2100, utilise existing desalination (150ML/day))	Moderate demand management (per-capita demand reduced to 150 L/p/d, leakage reduced to 422 ML/day by 2100, utilise existing desalination (150ML/day))	Medium demand management (per-capita demand reduced to 130 L/p/d, leakage reduced to 422 ML/day by 2100, utilise existing desalination (150ML/day))	Supply side prioritisation (no demand side management, utilise existing desalination (150ML/day), re-use (150ML/day in 2030), new reservoir (63ML/day 2040 + 102ML/day in 2070))	Mixed portfolio (per-capita demand reduced to 150 L/p/d, leakage reduced to 422 ML/day by 2100, utilise existing desalination (150ML/day), re-use (150ML/day in 2050))	Increased consumption (per-capita demand increased to 180 L/p/d by 2080, utilise existing desalination (150ML/day), re-use (150ML/day in 2030) net increase in imports (29ML/day), new reservoir (63ML/day 2050 + 102ML/day in 2070).

3.5.1 Adaptation pathways

Pathways were selected to represent a range of adaptive strategies that stakeholders considered informative. The actions in the six portfolios were scheduled to investigate a range of potentially feasible timescales over which adaptation options could be

implemented at scale. The portfolios were combined with two population growth scenarios to generate 12 pathways. We investigated the impacts of population growth using two transient scenarios, consistent with the Office for National Statistics baseline and high growth population projections, generated using the method described in Zuo et al. (2014). The existing number of residents in the LWRZ is approximately 7.1 million. The high growth population scenario corresponds to a peak population of 9.3 million in the LWRZ in 2070 primarily driven by strong in-migration, whilst in the baseline scenario population peaks at 8.4 million in the early 2060s.

A portfolio of indicators can be used to provide evidence that a certain condition exists or certain results have or have not been achieved (Pringle, 2011). Water resources studies have traditionally focused on somewhat abstract metrics, such as margins between supply and demand, which cannot be directly related to observable states of a system (Hall et al., 2012d). Risk-based metrics, on the other hand, make explicit the probability of observable states of the system (e.g., water shortages) occurring at a range of timescales and in response to alternative management actions. Incorporating risk-based metrics in the appraisal of adaptation actions provides a way of comparing risks and costs so that adaptation pathways that are proportionate to the levels of risk may be identified (Hall et al., 2012a).

In the LWRZ water shortages of different levels of severity are triggered by water storage levels, which can be directly measured and simulated. While stakeholders would rather not incur restrictions on water use, it is recognised that 100% reliability of supply is not possible. Tiered water-use restrictions are introduced to reduce demand and hence the likelihood of further restrictions becoming necessary.

Based on the frequency of shortages users will tolerate and their willingness to pay to reduce the frequency of shortages (Willis et al., 2005), water utilities have established a target frequency of water use restrictions for shortages of varying levels of severity, as per Table 3-2. A level 3 Temporary Use Ban is estimated to result in a £4.3–9.5m per day cost for London, with a level 4 Emergency Drought Order costing £236m (NERA, 2012). These restriction levels were adopted as they are central to existing decision-making approaches for managing water security.

Table 3-2 Target frequency of water restrictions in the London Water Resource Zone based on the frequency of shortages users will tolerate and their willingness to pay to reduce shortages (Thames Water, 2014)

	Water restriction	Target frequency
Level 1	Media campaign	1 in 5
Level 2	Hosepipe ban	1 in 10
Level 3	Temporary use ban	1 in 20
Level 4	Emergency drought order	1 in 1000

Given the uncertain nature of existing and future social and hydro-climatic conditions, it is not possible to determine if target frequencies will be achieved - at best we may estimate the probability of exceeding them (Borgomeo et al., 2014). As such, the probability of exceeding the target frequency for each level of water restriction is our proposed metric of water-supply risk.

3.5.2 Appraisal and visualisation

A transient version of the UKCP09 Weather Generator (WG) was used to generate time series inputs for rainfall and potential evapotranspiration (PET) to 2100 (Glenis et al., 2015). The weather generator is conditioned upon a large ensemble of future climate conditions obtained from the UKCP09 climate projections (Murphy et al., 2009). These projections were generated from a large perturbed physics ensemble of the Met Office

Hadley Centre's HadCM3 GCM, as well as incorporating evidence from other climate models around the world. One hundred realisations of the stochastic WG conditioned on 100 different vectors of change factors (i.e., different future climates) sampled from the full range of the UKCP09 probability distribution resulted in a total 10,000 time series of future climates. More details on the UKCP09 projections can be found in Murphy et al. (2009). River flow was simulated using CATCHMOD, a lumped rainfall-runoff model developed by the EA that converts daily rainfall and PET time series into daily stream flow (Wilby et al., 1994, Wilby, 2005). A simplified version of the water supply infrastructure in the of the LWRZ was represented using IRAS-2010 water resources system model (Matrosov et al., 2011). Emission scenario uncertainty, hydrological model structural uncertainty, land-use change uncertainty, changes in water abstraction licencing, the impacts of climate change on water demand, social uncertainties including the changing perspectives of decision makers and economic uncertainties are not considered in this appraisal.

As described in Borgomeo et al. (2014), the output from each simulation is a record of the annual frequency of water shortages of different levels of severity. The output from the simulations is combined to generate a distribution of the annual frequency of water shortages, which is compared to the target frequency of 'restrictions' (shown in Table 3-2) to estimate the probability of exceeding the target frequency for four levels of water restriction in each year of the planning period. Costs for individual actions are based on TW's (2014) publicly available cost estimates. Financial costs reflect the present value of capital expenditures incurred to build each option and the expenditures associated with the option's operation, a simple cost estimation model was used to calculate the present value of each pathway for a range of discount rates consistent with UK Treasury Guidance (2011). Sensitivity to these cost estimates should be explored

further. Adaptation pathways diagrams were developed and include four components: an indicator of the changing climate hazard; an exposure indicator; a dynamic adaptation portfolio; and, a quantified risk index varying through time.

3.6 RESULTS

We have defined risk as the probability of exceeding the target frequency for water use restrictions. Figure 3-6 to Figure 3-6 show the effectiveness of the pathways in managing water supply risk, under a high population growth scenario. Differences in the pathways' investment profiles are shown in the transient risk profiles. In Pathway 6, for example, the commissioning of a large reservoir in the 2070s results in a sharp reduction in risk, whilst distributed demand side actions in Pathways 2 and 3 have a more gradual and moderate impact on the changing level of risk. Transient population projections peak in the 2070s, which corresponds with peak modelled levels of risk. The minor fluctuations in the levels of risk are a result of the stochastic climate change projections used in the risk calculation.

The probability of exceeding the target frequency for Level 1 water restrictions is currently less than 0.1 and less than 0.01 for Levels 2–4 (black line in Figure 3-6). Stakeholder consultations indicated that there is no desire to increase the level of risk within the system, but existing levels of risk are acceptable, and as such we have adopted an acceptable threshold risk level of 0.01 for Level 2 to 4 water restrictions. For a Level 3 water shortage, this implies that decision-makers consider a 0.01 probability of having to impose a water use restriction more frequently than once in 20 years as acceptable. Our appraisal identified that Pathways 3, 5 and 9–11 are capable of maintaining risk below this threshold to 2100 under a medium emissions scenario for London.

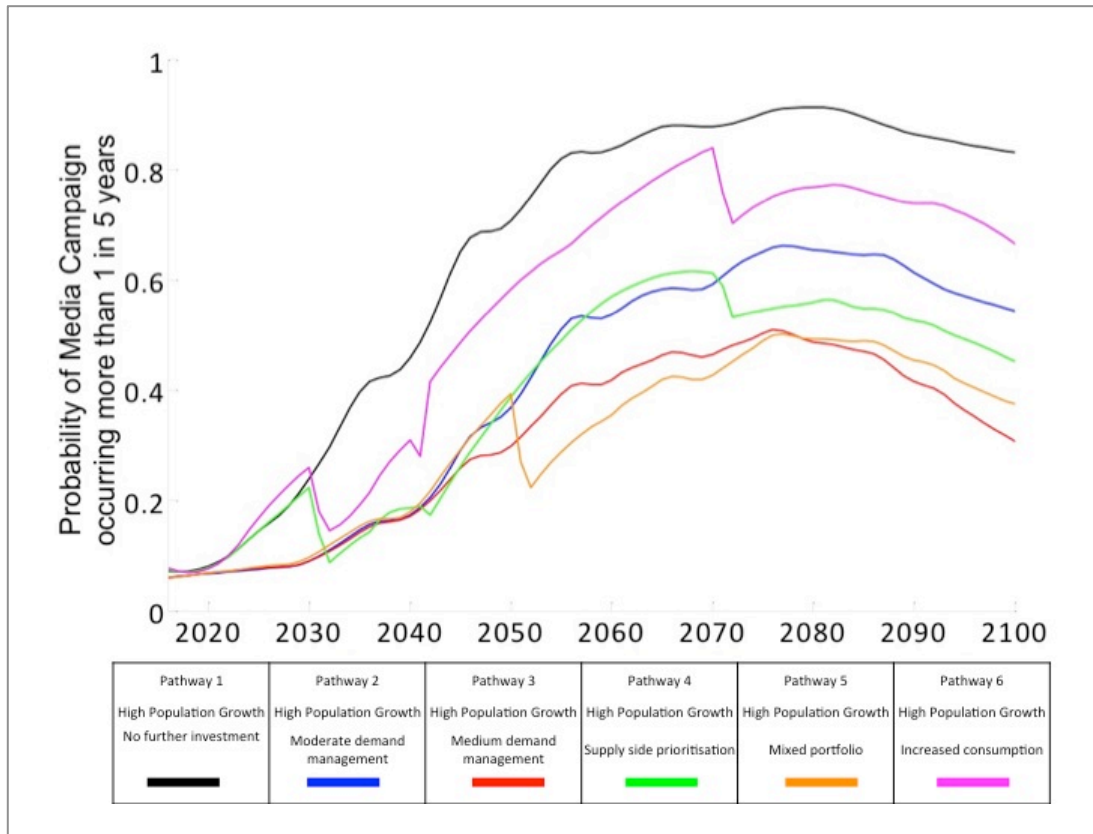


Figure 3-3 Appraisal of the effect of Adaptation Pathways 1-6 on the probability that a media campaign is required more than Thames Water's target level of one in five years

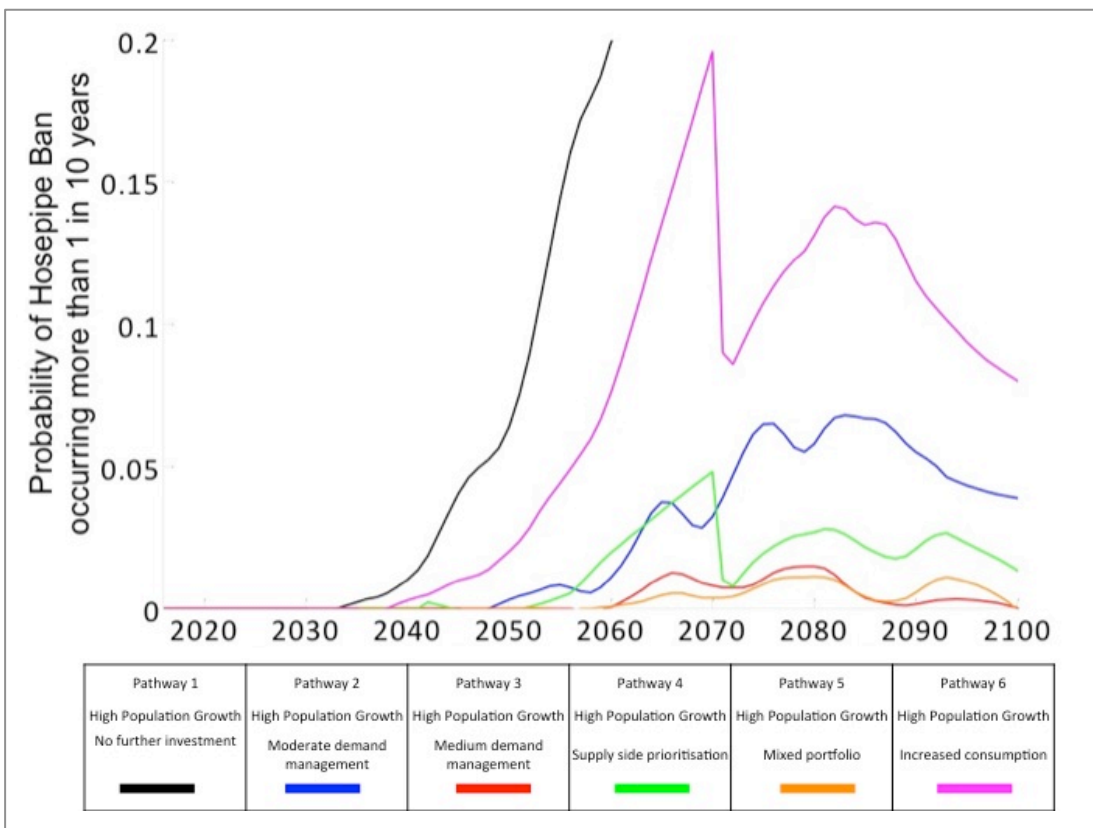


Figure 3-4 Appraisal of the effect of Adaptation Pathways 1-6 on the probability that a hosepipe ban is required more than Thames Water's target level of one in 10 years

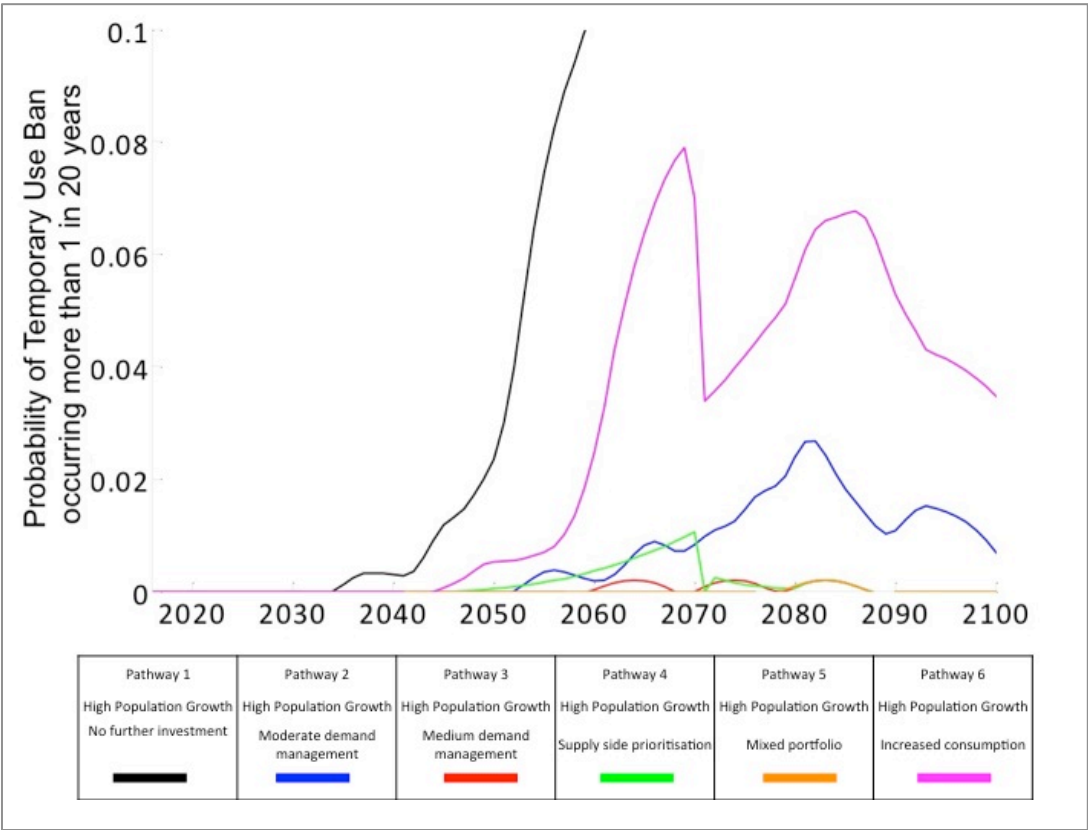


Figure 3-5 Appraisal of the effect of Adaptation Pathways 1-6 on the probability that a temporary use ban is required more than Thames Water's target level of one in 20 years

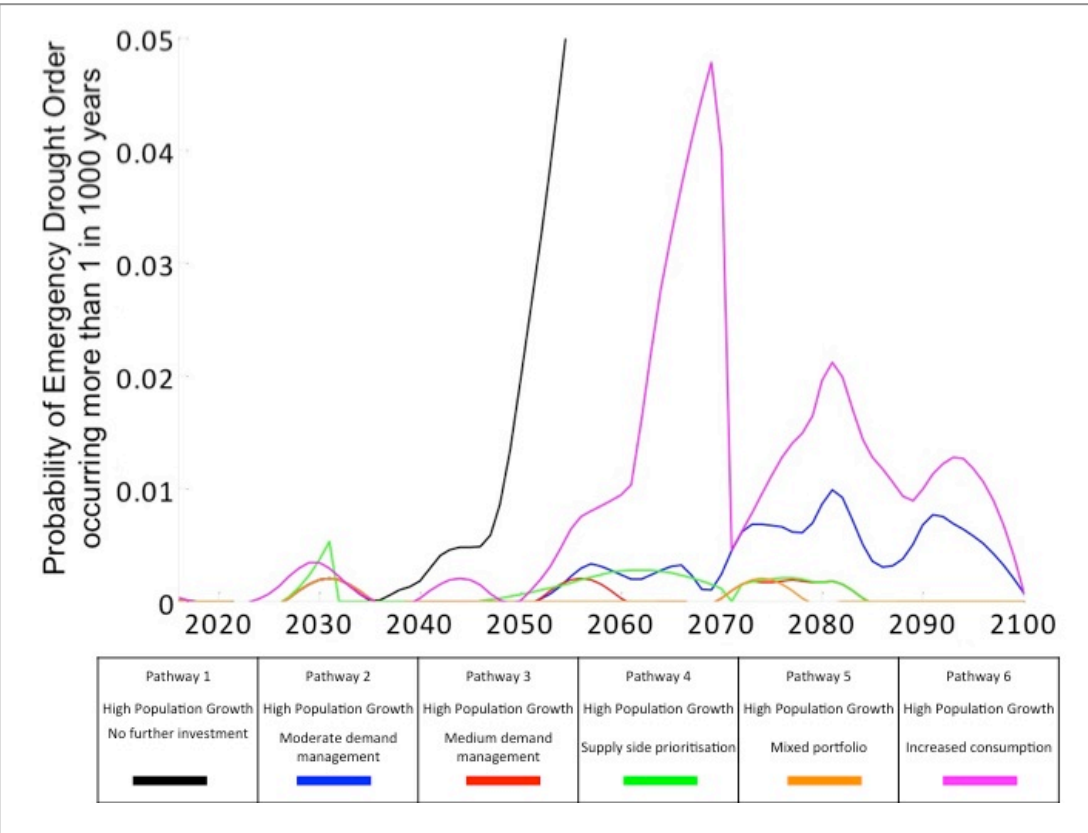


Figure 3-6 Appraisal of the effect of Adaptation Pathways 1-6 on the probability that an emergency drought order is required more than Thames Water's target level of one in 1000 years

Without further investment (Pathway 1 – black line in Figure 3-6), the level of risk will exceed the acceptable threshold. In the high population growth scenario there is a 0.75 probability that media campaign (Level 1) water restrictions will occur more than once every 5 years by 2050. This would lead to a significant increase in the utilisation of the existing energy intensive desalination plant, which is activated during Level 1 restrictions. This highlights the importance of considering the interactions between adaptation and mitigation in drought response and long-term planning.

Without adaptation, we observe very rapid increases in water supply risk in Figure 3-6. This highlights that ongoing investment will be required in the LWRZ, and given the rate of increase in risk and the long lead-time in implementing many adaptation actions, anticipatory adaptation will be required.

Our research supports the notion that London's future water supply risk could be maintained below an acceptable threshold with demand side actions. Demand side management approaches are flexible, as they do not require a single commitment to supply infrastructure that could be mal-adaptive. There is a high degree of uncertainty regarding the effectiveness of demand management actions. A pathway that increases the reliance on per-capita demand reduction must place a high priority on monitoring the outcomes of adaptation action in reducing demand. A lack of progress in reducing demand up to 2030 may indicate that pathways that rely significantly on demand reduction need to be reconsidered; alternatively successful demand reduction may prompt consideration of pathways with even more aggressive demand reduction.

Stakeholders identified that strategic decision-making is most strongly influenced by low frequency high consequence events – an 'emergency drought order' currently has a target frequency of 'never' (Thames Water, 2014). We adopted a target frequency of

failure of 1 in 1000 years in our analysis to reflect the significant implications of an emergency drought order on individual customers and strategically for London. From a London perspective, this provides consistency with the design return intervals for its estuarine flood defences. Our analysis identified Pathways 3–5 as capable of keeping the probability of exceeding the target frequency of an emergency drought order below 0.01, through to 2100 under a medium emissions scenario.

Costing is an important consideration in identifying trade-offs for adaptation decision-making. The present value (PV) cost of the actions included in Pathways 1–12, for a range of discount rates, was calculated to provide an initial estimate of the relative cost of each pathway, as per Table 3-3. The costs are in addition to the existing costs of managing the system. The PV includes capital and operational expenditure and is dependent on the specified level and timing of investment.

Under a high population growth scenario Pathways 3–5 are most effective in managing risk. A supply side prioritisation portfolio is more expensive than moderate demand management or a mixed portfolio with a discount rate of 4.5%. It is less expensive however, with a lower discount rate of 3.5% or 2.5%. This change in ranking highlights the sensitivity of the decisions to discount rates and further investigation is suggested (Mortazavi-Naeini et al., 2014).

The development of long-term adaptation pathways is presented as an iterative process, as per Figure 3-1. Following the pathways appraisal phase, feedback from stakeholders should be sought to identify if sufficient input to the specification of an adaptive plan has been achieved. As a demonstration case study we only completed one iteration; however, if this approach were adopted multiple iterations may be required.

Table 3-3 Present value cost estimate of Adaptation Pathways 1–12 (2015–2100)

Additional Investment – PV (£ millions)							
Discount rate	4.5%	Rank	3.5%	Rank	2.0%	Rank	
No further investment High Population Growth	£ -	1	£ -	1	£ -	1	
Moderate demand management High Population Growth	£ 371	2	£ 507	2	£ 879	2	
Medium demand management High Population Growth	£ 439	5	£ 620	6	£1,129	6	
Supply side prioritisation High Population Growth	£ 444	6	£ 586	4	£ 929	4	
Mixed portfolio High Population Growth	£ 437	4	£ 609	5	£1,074	5	
Increased consumption High Population Growth	£ 392	3	£ 536	3	£ 900	3	
No further investment Baseline Population Growth Baseline Population Growth	£ -	1	£ -	1	£ -	1	
Moderate demand management Baseline Population Growth	£ 309	2	£ 422	2	£ 729	2	
Medium demand management Baseline Population Growth	£ 416	4	£ 585	4	£1,059	6	
Supply side prioritisation Baseline Population Growth	£ 444	6	£ 586	5	£ 928	4	
Mixed portfolio Baseline Population Growth	£ 429	5	£ 596	6	£1,048	5	
Increased consumption Baseline Population Growth	£ 392	3	£ 536	3	£ 900	3	

Figure 3-7 shows one example pathway diagram for the LWRZ mixed portfolio (Pathway 5). It highlights the dynamic nature of water risk and its relationship with adaptation actions. The risk-based metric integrates the impact of multiple drivers of changing risk including stream flow, population, per-capita demand, and adaptation actions. The central component of Figure 3-7 highlights a dynamic portfolio of adaptation actions. The timing, rate and scale of implementation of demand management actions have been scheduled alongside a new water re-use plant. During the period 2015–2040, leakage reduction and enhanced water metering manage risk within acceptable levels. Beyond this period, risk increases until a reuse plant is commissioned in 2050, which corresponds to a sharp decrease in risk. The climate hazard and exposure indicators reinforce the links between changes in society, climate and adaptation action. From 2070 to 2100 risk decreases as population decreases.

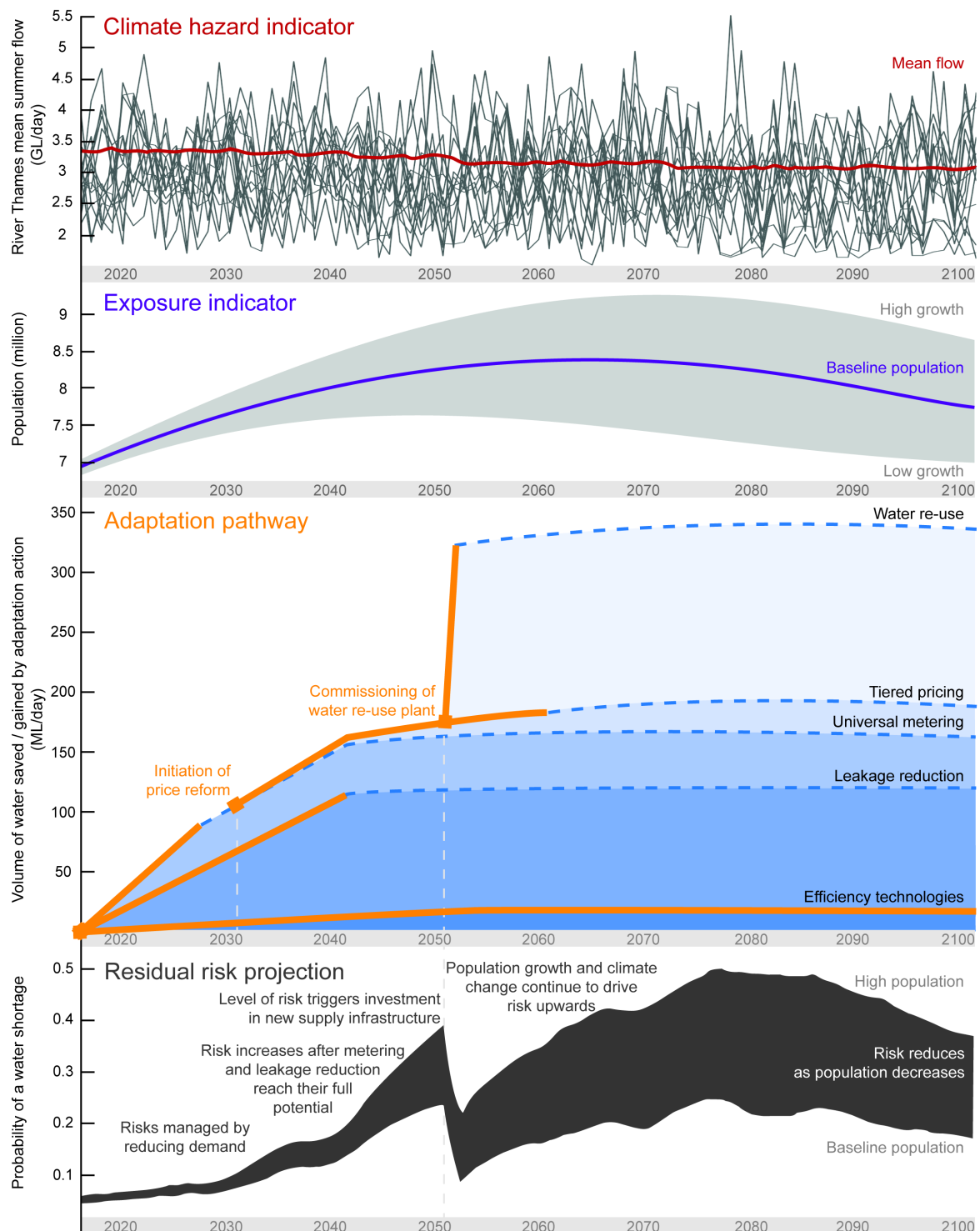


Figure 3-7 Adaptation pathway diagram for water resource management in London. This pathway quantifies the effectiveness of a mixed portfolio of supply and demand side actions implemented up to 2100 (Pathway 5). The range in the risk results reflects the difference between the high and baseline population growth scenarios.

3.7 DISCUSSION AND CONCLUSION

The adaptation pathways approach demonstrated in this paper complements existing water resource management approaches to extend planning beyond current mid-term horizons. Building consensus on the need for adaptive action and how to best implement it is difficult and it requires commitment to a long-term strategic approach (Barnett et al., 2014). Demonstrating that a system could cope with future changes, even if we don't need to act now, provides confidence that systems are able to cope with long-term risk. A long-term plan reduces the likelihood of mal-adaptation and undesirable lock-in, creates awareness of the dynamic nature of the climate system, and builds the political and business case for integrating flexibility into infrastructure planning (Ranger et al., 2013). For example, future adaptations may require preparatory actions in the short-medium term, such as setting aside land for reservoirs.

The aim of this study has been to demonstrate an adaptation pathways method that may inform adaptation planning for London's water resources, rather than develop London's long-term water resource management plan. The development of London Water 2100 or an equivalent long-term plan would require more extensive consultation and the consideration of a broader range of perspectives and decision criteria. Initial stakeholder feedback found the pathways diagrams to be a potentially valuable input to long-term planning.

We used multiple versions of pathways diagrams to present quantified transient scenarios outlining the trade-offs between risk and investment in adaptation actions to facilitate conversations about different futures, Pathways 3 and 4 are included in Figure 3-8 and Figure 3-9 respectively. Stakeholders found that our method created a 'free thinking space' for the unrestricted consideration of actions that may not be politically

or financially acceptable in the near-term. In this thinking space, the implications of prioritising flexible actions as a means of achieving robust outcomes can be explored in focus group discussions. Pathway 3, for example, is more flexible than a portfolio consisting of two new reservoirs and a re-use plant (Pathway 4), but it is more expensive.

An adaptation plan is considered robust if it performs adequately across a broad range of plausible climate, population and investment scenarios (Wilby and Dessai, 2010). Considering portfolios of actions provides the flexibility to cope with a variety of possible future conditions and can help to compensate underperformance of any particular action. A pathways approach contributes to the development of dynamically robust plans by incorporating flexibility in the scheduling and implementation of actions, and allowing changing levels of risk to inform future decisions.

Residual uncertainty from the risk-based appraisal may be addressed by adopting a pathways approach. The pathways approach, by reinforcing the role of ongoing monitoring of decision triggers and prioritising flexible actions, puts decision makers in a better position to respond to future conditions beyond those projected. If flow conditions are outside the range considered, water managers retain the ability to increase the frequency and level of water restrictions up to and including emergency drought orders. To avoid increasing restriction frequency, flexible pathways should be updated as new climate and socio-economic information becomes available. If the frequency of water restrictions increases beyond acceptable levels additional adaptation actions should be brought forward.

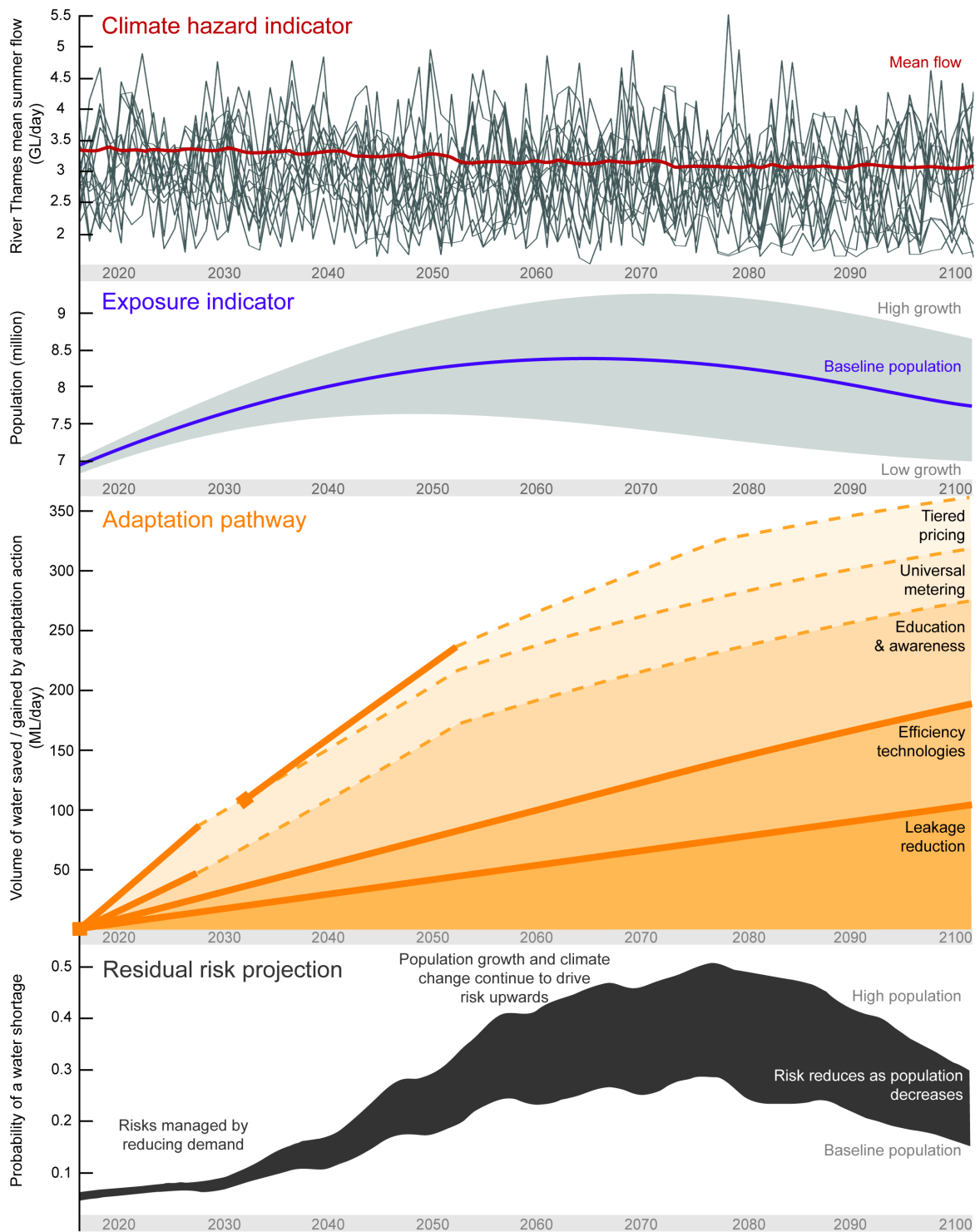


Figure 3-8 Adaptation Pathway 3 for water resource management in London. This pathway quantifies the effectiveness of a portfolio of demand side management actions implemented up to 2100. The range in the risk results reflects the difference between the high and baseline population growth scenarios.

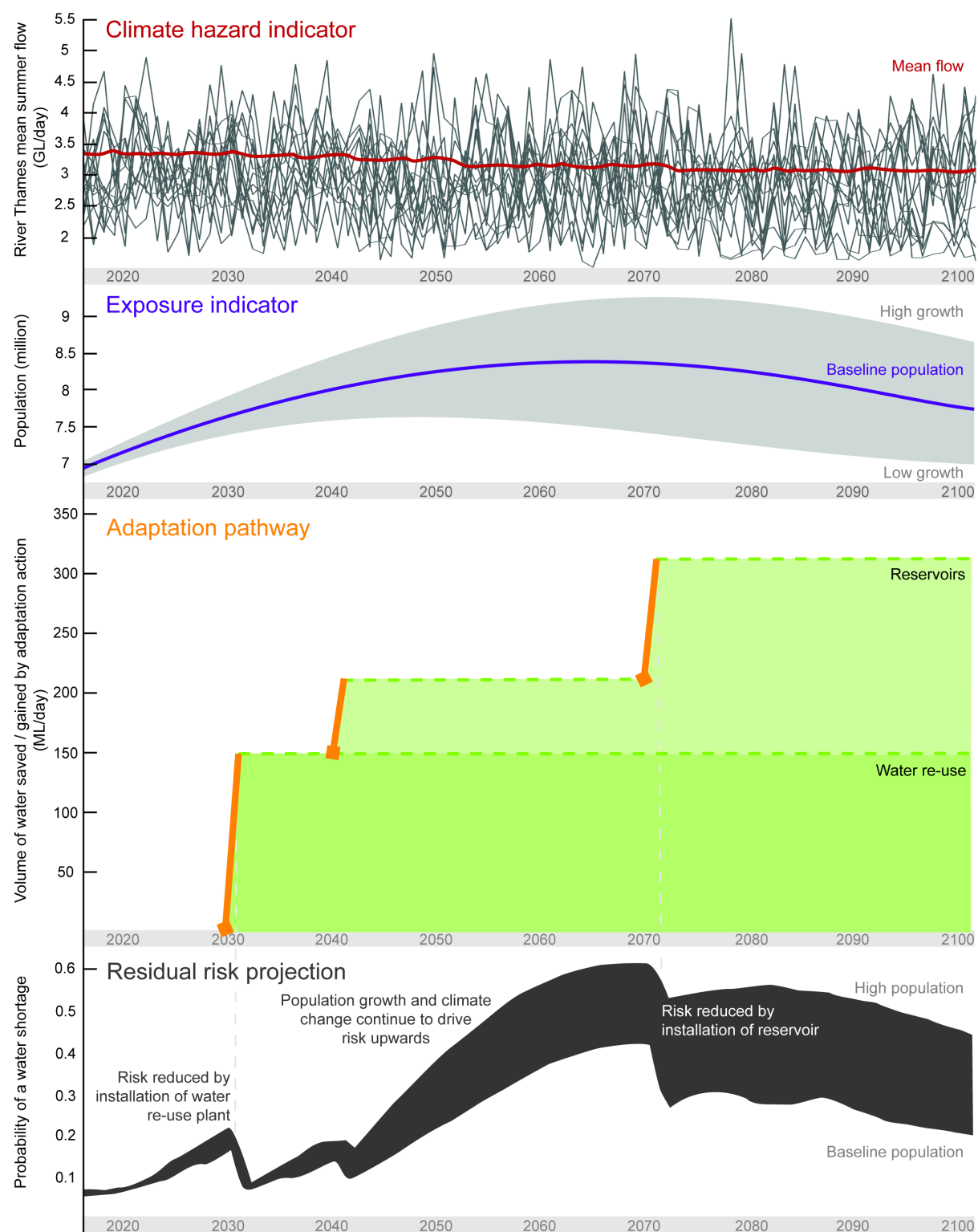


Figure 3-9 Adaptation Pathway 4 for water resource management in London. This pathway quantifies the effectiveness of a portfolio of capital-intensive supply side management actions implemented up to 2100. The range in the risk results reflects the difference between the high and baseline population growth scenarios.

This study has co-developed a range of adaptation pathways as scenarios to inform long-term decision-making, addressing a number of challenges in linking existing and long-term approaches to planning. However, the application of a risk-based approach to the development of adaptation pathways remains challenging. Water resource planning in London is undertaken by water companies in accordance with the Water Resource Planning Guidelines (EA et al., 2012) and within this structure there are limited incentives for companies to implement approaches that are more complex and/or resource intensive than those required. However, water companies, including TW, have expressed interest in better understanding the potential for implementing long-term pathways approaches and UK's water resource planning guidelines are updated periodically, which opens the door to integration of such methods in future planning periods. In London, low regret and flexible demand-side management actions along with continued efforts to reduce leakage should be prioritised in the short term. Depending on population growth and climate change supply-side options may be needed in decades to come, so preparatory action should begin now.

Identifying acceptable and tolerable levels of risk is a key component of a pathways approach because of its direct link to the timing and scale of future investment; however, feedback from stakeholders indicated that further understanding of the implications of varying acceptable and tolerable levels of risk is required. Future pathways research could utilise optimisation approaches to identify the pathways that perform best for the specified input assumptions across a range of risk thresholds (Mortazavi-Naeini et al., 2014, Beh et al., 2015, Matrosov et al., 2015), as demonstrated for medium term planning by Borgomeo et al. (2016). Risk thresholds will change through time depending, in part, on how severe future water shortages are, on how these risks compare with the costs of adaptation (Yohe and Leichenko, 2010,

Wade et al., 2013, Hall and Borgomeo, 2013) and on how decision makers' values change (Haasnoot et al., 2012). Exogenous scenarios can be used to further explore socio-economic uncertainties, such as future risk thresholds, when exploring pathways with water managers.

Our adaptation pathways diagrams were developed to link components of risk assessment, monitoring and evaluation, and adaptation decision-making. Risk is mapped directly below each adaptation portfolio in the pathways diagrams to highlight the way in which future risk is coupled with adaptation actions. Integrating and institutionalising monitoring is a critical component of adaptation decision-making that has not received sufficient attention. Adopting risk-based thresholds as triggers for decision-making will require monitoring a range of indicators, as risk is not directly observable. For London's water supply, indicators such as storage level and rate of demand, as well as climate hazard indicators to inform risk monitoring, are required. Monitoring the frequency of droughts nevertheless remains difficult due to the lack of observations of extreme events. Large ensemble climate experiments, similar to those used in attribution studies, provide an opportunity to quantify the changing probability of extreme events (Kay et al., 2011, Pall et al., 2011). Such an approach could be used to probabilistically represent the current climate and identify the probability of tolerable levels of risk being exceeded, given the observed characteristics of the water system. The uncertainty in climate projections arising from climate model uncertainty and emission scenario uncertainty, the latter being particularly relevant for the long timescales considered in adaptation pathways, mean that any probabilistic analysis of the type presented in this study may be complemented by robustness testing of assumptions and uncertainties (Moody and Brown, 2013, Nazemi and Wheeler, 2014, Herman et al., 2015). As part of an adaptive planning approach, the adaptation

pathways should be updated when new information becomes available in future planning cycles.

This study has demonstrated an innovative approach to the development of adaptation pathways that responds to increasing water supply risk. We have quantified how risk varies dynamically for a range of adaptation pathways over time with climate change and population growth and we have demonstrated how transient probabilistic climate change projections can be used to extend water resource planning horizons to 2100.

Governments can apply this framework through a combination of mainstreaming as well as long-term adaptation planning. Initial recommended actions include: (i) adopting a risk-based approach to water resource planning; (ii) identifying and monitoring risk-based decision triggers; (iii) including robustness and flexibility metrics into existing decision appraisal; and (iv) utilising transient scenarios to inform the timing of adaptation actions. Priorities for developing long-term adaptation plans include the identification and exploration of a series of plausible long-term adaptation pathways.

Future water resource decision-making will continue to be a process of managing trade-offs in a complex dynamic risk landscape, and implementing actions as necessary to manage water supply risk. The implementation of these actions over time will result in an adaptation pathway. London's ability to remain a world-leading city in an increasingly globalised economy is dependent on it being an efficient and low risk place to do business and desirable place to live. London and other cities internationally will increasingly need to develop and implement adaptation strategies that consider multiple long-term climate risks. This adaptation pathways approach demonstrates an effective framework for informing such long-term adaptation planning.

4 Development and appraisal of long-term adaptation pathways for managing heat-risk in London

4.1 INTRODUCTION

Adapting to increasing mean and maximum temperatures, and heat waves that are projected to increase in both frequency and severity, is a significant challenge for urban authorities globally (Hunt and Watkiss, 2010, IPCC, 2014). Without proportionate adaptation, increasing heat-risk is likely to result in increasing heat-related mortality (Gasparrini et al., 2015, Hajat et al., 2014, Stone et al., 2014, Taylor et al., 2015b); additional residential overheating (Porritt et al., 2012, Taylor et al., 2015b, ZCH, 2015); reduced infrastructure performance (Jenkins et al., 2014a); and, in extreme cases, it may exceed the threshold for human adaptability and threaten the viability of cities (Pal and Eltahir, 2015).

Adaptation actions may include physical, behavioural and policy-based measures that reduce climate risk, alter drivers of social vulnerability, deliver adaptation benefits, or build adaptive capacity. Adaptation pathways are a policy-first approach to decision-making that targets analysis at directly informing the adaptation decision problem (Ranger et al., 2010a). A pathways approach that sequences the implementation of actions over time, to ensure the system adapts to the changing social, environmental and economic conditions, will build flexibility into the overall adaptation strategy

(Ranger et al., 2010a, Haasnoot et al., 2012). An adaptation pathway provides a visual representation of the potential sequencing and type of actions that may be implemented in the future (Kingsborough et al., 2016).

The combined effects of the urban heat island (UHI) and global warming are projected to significantly increase summer temperatures and the number of heatwaves³ in London (McCarthy et al., 2010, Mavrogianni et al., 2011, Murphy et al., 2009). A heatwave equivalent to the 2003 heatwave – which resulted in 650–1000 excess deaths in London (D'Ippoliti et al., 2010) – is projected to have a return period of 1 in 2 years in the 2080s, under a medium emissions scenario at the 50% probability level (Murphy et al., 2009, LCCP, 2012a).

While the risk of mortality due to heat in London remains lower than that due to cold (Gasparrini et al., 2015), heat-risk is expected to increase as the climate warms and extreme heatwave events become more common (Jenkins et al., 2014b, Taylor et al., 2015b, Wolf and McGregor, 2013). Heat-risk associated with increased mortality and overheating of people, buildings, infrastructure and urban environments is increasing and needs to be addressed through adaptation (Nickson et al., 2011, LCCP, 2012b, LCCP, 2012a, Hajat et al., 2014, Jenkins et al., 2014a, Jenkins et al., 2014b, ZCH, 2015, Taylor et al., 2015b).

Limited research exists that estimates the vulnerability of populations to heat-risk based on a combination of population and environmental variables at the city scale (Taylor et

³ Two heatwave definitions are commonly used in London: Public Health England define a heatwave (Level 3) as two consecutive days above 32°C with an overnight minimum above 18°C (2015), while the London Resilience Partnership define it as five days above 32°C with overnight minimums above 15 degrees (2014).

al., 2015b). Wolf and McGregor (2013) used principal components analysis to create a heat vulnerability index for London that accounted for UHI, living in a flat, population density, age, illness, socio-economic status, social isolation, and ethnic minority status. They found spatial clustering of areas of high heat vulnerability in Central and East London that coincide with areas of potentially high heat exposure. Taylor et al. (2015b) examined the risk of mortality in London during hot weather events by combining data on population age and distribution, UHI, and dwelling characteristics to calculate the spatial variation in heat-related mortality risk across London. Spatial variation of heat-related mortality was found to reflect background mortality rates due to population age, while dwelling characteristics were found to cause a larger variation in risk than the UHI. This research, however, did not consider future climate, socio-demographic or adaptation scenarios.

Jenkins et al. (2014b) utilised high spatial resolution probabilistic projections of urban temperatures with projections of demographic change as part of a risk assessment at the ward scale in London. They found that reducing indoor temperatures by 1–2°C reduced both annual heat-related mortality and residential overheating compared to no-adaptation in future scenarios, however limited consideration was given to the nature and feasibility of potential adaptation actions.

A range of actions including land-use planning, building design, community resilience, and emergency planning and response must be considered together for cities to manage long term heat-risk. Research on the effectiveness of localised adaptation actions in London is growing, including solar shading; building insulation and ventilation (Porritt et al., 2012); roof insulation and window upgrades (Mavrogianni et al., 2012); green roofs (Virk et al., 2015, Virk et al., 2014); and occupant behaviour (Mavrogianni et al.,

2014). However, evidence on the effectiveness of adaptation actions in lowering heat-related mortality is limited (Frontier Economics et al., 2013), and quantifying the effectiveness of specific adaptation options into an associated temperature based increase in resilience at the city scale remains a significant challenge (Jenkins et al., 2014b). There is limited research on existing and future heat-risk that actively considers the effectiveness of specific adaptation actions in managing that risk over time at the city scale (Stone et al., 2014).

Adaptation pathways have demonstrated significant potential as an adaptation planning approach and been used in a range of contexts, with a focus on the water sector (Haasnoot et al., 2012, Barnett et al., 2014, Rosenzweig and Solecki, 2014, Lawrence et al., 2013, Siebentritt et al., 2014, Wise et al., 2014, Haasnoot et al., 2013, Kingsborough et al., 2016). They have not been applied to long-term planning for urban heat-risk at the city scale, and a lack of demonstration in this context limits decision-makers' confidence in their utility. There is a need to continue developing, trialling, critiquing and demonstrating how pathways approaches can be utilised in informing and motivating adaptation planning (Haasnoot et al., 2012, Wise et al., 2014, Barnett et al., 2015, Kingsborough et al., 2016).

This research adopts a framework for adaptation planning and the development of adaptation pathways developed by Kingsborough et al. (2016); generates quantified estimates for the effectiveness of a range of adaptation options; and utilises an updated probabilistic spatial heat-risk assessment model developed by Jenkins et al. (2014b) to demonstrate how adaptation pathways may manage long-term heat-risk in London. We present a quantified assessment of how heat-risk in London is projected to vary depending on the choice of adaptation pathway under a medium climate and population

scenario. This research focuses on Greater London: assessing mortality risk, thermal discomfort in residential buildings, and adaptation pathways.

4.2 METHODOLOGY

The adaptation planning framework developed by Kingsborough et al. (2016) is a risk - based and iterative approach that prioritises management of existing risks, and guides the development of long-term adaptation pathways. Within our adaptation planning framework (Figure 3-1), the key steps in the development of adaptation pathways include: a review of the potential usefulness of adaptation pathways; the identification of an adaptation canvas; selection of adaptation portfolios; the development of adaptation pathways; and an appraisal and visualisation of adaptation pathways. This section outlines their application to the development of adaptation pathways for heat-risk.

4.2.1 Review

A policy and document review of risk management, governance and planning approaches in London was undertaken to better understand the extent to which existing and future heat-risk is considered; identify relevant planning horizons; establish decision criteria and risk thresholds; and understand stakeholder perspectives on the potential value in developing long-term pathways. Semi-structured interviews were also conducted with stakeholders from the Greater London Authority (GLA) and the Environment Agency London Team to identify near and long-term priorities, ways in which they may or may not be affected by climate change, and perceived barriers and enablers in adapting to changing heat-risk. Multiple meetings of the London Climate Change Partnership (a collection of organisations that contribute to increasing

London's climate change preparedness) and the London Working Group on Heat-risk (a collection of organisations that share their experiences working to address heat-risk) were attended in 2013–2015 to further understand the context for adaptation planning in London.

4.2.2 Adaptation canvas

An adaptation canvas provides an opportunity to consider a wide range of adaptation actions, their possible limits and associated uncertainties in a visual manner that illustrates the potential solution space.

Figure 4-1 is a stylised causal loop diagram that identifies potential urban heat actions, the relationships between the actions and the nature of the impact of each action on mortality and residential discomfort. The actions are grouped according to the spatial scale at which they are most applicable.

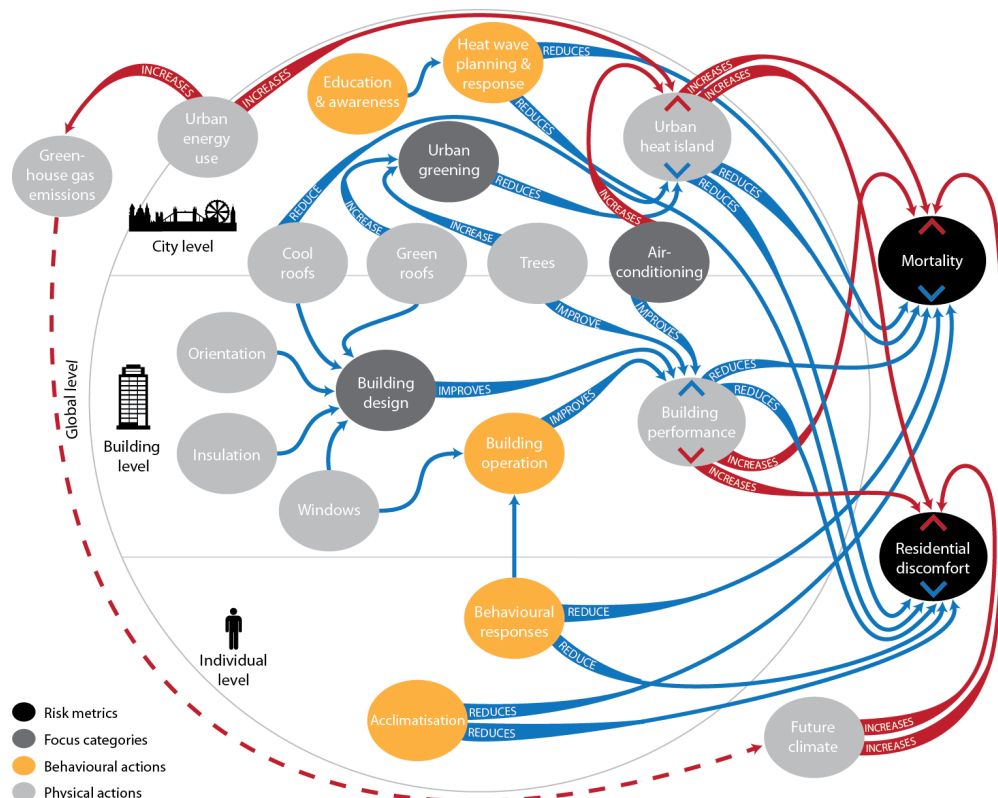


Figure 4-1 A stylised causal loop diagram that identifies potential urban heat actions, the relationships between the actions and the nature of the impact of each action on mortality and residential discomfort.

This paper focuses on three categories of adaptation action – urban greening, air-conditioning, and upgrading the building stock – as not all of the identified adaptation actions could be considered within the scope of this research. The selected actions were identified as potentially having a long-term impact on the heat-risk level at the city scale; interesting to stakeholders; and quantifiable. As we completed a quantitative appraisal of the adaptation pathways, the methodological steps to develop plausible estimates of the effectiveness of selected adaptation actions and their implementation potential are also described below.

Early warning, emergency response, communication and stakeholder engagement actions (PHE, 2015, Matthies and Menne, 2009, Hajat et al., 2010, Wolf and McGregor, 2013), and the supporting institutional structures and capacities (Zaidi and Pelling, 2015) play a valuable role in managing the impacts of heat-risk on individuals and communities. However, due to the dearth of reliable data on the costs and effectiveness of heatwave response planning (Frontier Economics et al., 2013) and research on the effect of behavioural adaptation on vulnerability (Zaidi and Pelling, 2015) these actions are not appraised further in this research, whilst it is acknowledged they will form an important component of future adaptation portfolios.

4.2.2.1 Urban greening

Observational and modelling studies have found vegetative cover and high-albedo materials to be associated with lower surface and near-surface air temperatures than sparsely vegetated areas with low albedo (Stone et al., 2014, Hart and Sailor, 2009, Virk et al., 2014, Li et al., 2014). The shading and evapotranspiration provided by trees and green spaces may reduce air temperatures and surface temperatures by 2–8°C in cities (ARUP, 2014). Green space accounts for 47% of Greater London (GiGL, 2014)

and current levels of greening are estimated to reduce night temperatures by 2–3°C (Mavrogianni, 2014). Reducing Central London’s 598km² vegetated region by 152km² is estimated to increase average annual temperatures by 0.5°C, while increasing vegetation in London by 50% is estimated to decrease the average night time UHI by 0.6°C (McCarthy et al., 2010).

We used Equation 4-1 developed by McCarthy et al. (2012) to estimate the impact of land-use change on temperatures in London. Change factors derived using Equation 4-1 were calculated for Central London, for five urban cover scenarios detailed in Table 4-1. The change factors were applied across Greater London by combining them with projections from a spatial weather generator (WG) (described in 4.2.5.1) to explore the cumulative impact of urbanisation and climate change. This approach has not previously been applied to a planning study or in the appraisal of adaptation actions.

$$\text{Equation 4-1} \quad \Delta T = B_1\chi + B_2\chi^2$$

χ = total urban land cover (in 100s of km²)

ΔT = temperature change (°C)

Coefficients B_1 and B_2 are specified in McCarthy et al. (2010).

We identified existing land-cover characteristics and developed five plausible scenarios of urban greening using spatial analysis of existing land-use categories in London from classifications in the MasterMap database (OS, 2015b), existing green space provisions in London from the GiGL land-type database (GiGL, 2014), and the GLA green roof database (GLA, 2014b).

Table 4-1 Plausible scenarios for urban greening and an example of the corresponding land-use changes that would be required to achieve each outcome

Scenario	Description
25% increase in vegetation cover	Vegetated garden areas increase 30% (multi-use land-type), greening of 50% of roofs and 25% of roadside areas, and no loss of existing green space.
25% decrease in vegetation cover	Paving of 15% of London's existing natural areas and 50% of all backyards.
Green roof saturation	The maximum estimated potential for green roof installation is 82% of the total roof area within the Victoria Business Improvement District (Rogers et al., 2012): an equivalent of 180km ² in Greater London.
50% increase in vegetation cover	Greening 82% of roofs, 75% of roadside areas and 70% increase in vegetated gardens (multi-use land-type).
50% decrease in vegetation cover	Paving of 60% of London's existing natural areas and 75% of all existing backyard vegetation.

4.2.2.2 Air-conditioning

Residential air-conditioning is a response to increasing summer temperatures or the occurrence of heatwaves, but its purchase is also typically influenced by economic and cultural factors (Sailor and Pavlova, 2003, Davis and Gertler, 2015). In the US, market saturation has increased from 2% in 1955 to now exceeding 90% (Sailor and Pavlova, 2003, EIA, 2011).

Whilst air-conditioning can deliver significant localised benefits in terms of reducing residential overheating, it is not a preferred adaptation action in London (GLA, 2011b) as the waste heat contributes to the UHI (Davies et al., 2008, Mavrogianni et al., 2011, McCarthy et al., 2012); it increases energy demand and greenhouse gas emissions (Day et al., 2009); and it is likely to be a costly and inequitable cooling solution (ASC, 2011). Heat released from energy use in present day London is estimated to account for approximately 15% of the average summer night time UHI of 2°C and 42% of the winter UHI of 1.2°C (McCarthy et al., 2012).

Air-conditioning is uncommon in London – an estimated 1–3% of households use fixed or portable air-conditioning units (Day and Opara, 2012, BRE, 2013) – but uptake is potentially rising, with one survey finding 6% of Londoners have installed air-

conditioning (ComRes, 2015). Given the current low levels of uptake and the projected change in climate there may be significant future increases in air-conditioning uptake. Figure 4-2 outlines our method to estimate the uptake of air-conditioning and the resultant impact on the UHI. We calculated the impact of waste heat emissions on the UHI for (i) scenarios of air-conditioning uptake driven by increasing temperatures under a medium emissions climate change projection (including feedbacks between the UHI and air-conditioning usage); and (ii) 50% and 100% air-conditioning uptake scenarios.

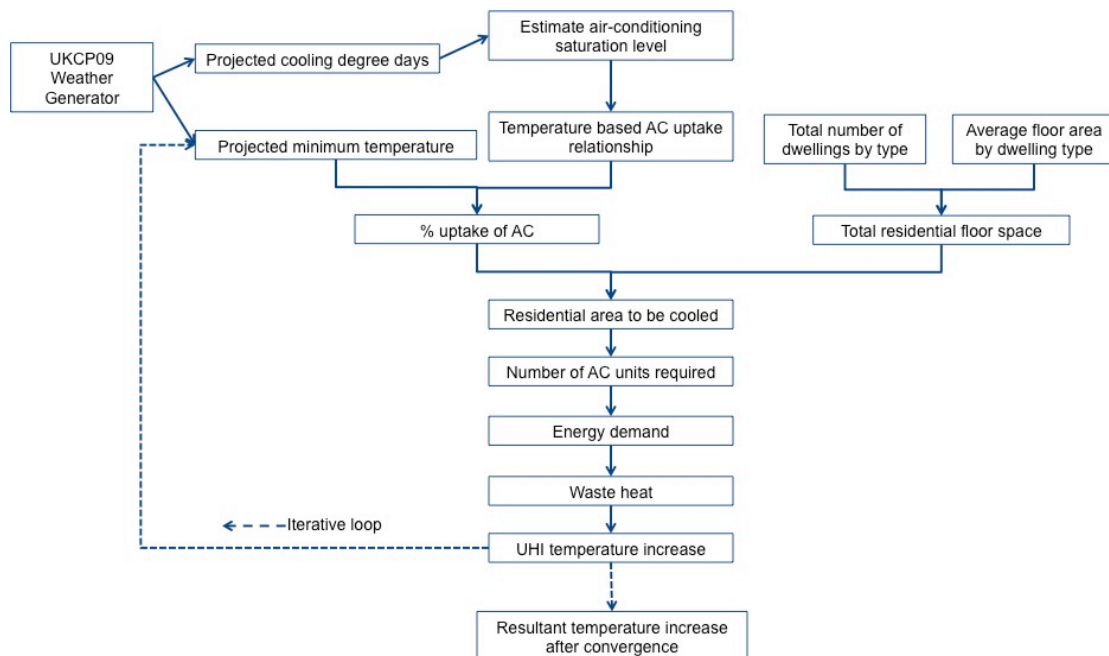


Figure 4-2 Outline of the method used to quantify the impact of air-conditioning on the Urban Heat Island, including a feedback loop between increases in temperature from waste heat and corresponding additional air-conditioning uptake

We used McNeil and Letschert's (2010) updated version of Sailor and Pavolva's (2003) relationship between cooling degree days (CDD) and air-conditioning market saturation for 39 US cities to estimate a market saturation (S) level for air-conditioning in London, as per Equation 4-2.

$$\text{Equation 4-2} \quad S = 1.0 - 0.949 \exp(-0.00187 \times CDD)$$

These regressions provided an initial estimate of potential air-conditioning uptake. This method has been used in a number of studies, including Riviere's (2009) national-level estimates for air-conditioning in Europe.

CDDs with a base temperature of 18°C (reflecting minimum temperature (Tmin) values used within heatwave definitions in London) were calculated using the UKCP09 WG and threshold detector (Murphy et al., 2009). In the 2080s high emission scenario the mean annual number of CDDs is 550 with an air-conditioning saturation level of 66%, which corresponds to an average summer Tmin of 17°C.

From this analysis a logistic growth model for air-conditioning, based on projected increases in summer Tmin, was created as per Equation 4-3.

$$\text{Equation 4-3 } \textit{Uptake of air conditioning} = \frac{1}{1 + e^{-(t-\mu)/\sigma}}$$

t = average summer Tmin

μ = temperature at which the rate of air-conditioning uptake peaks

σ = standard deviation of distribution

The values of μ and σ were chosen to produce an idealised growth pattern for air-conditioning uptake that corresponds to an existing level of air-conditioning of approximately 1% for an average summer Tmin of 12°C (as per UKCP09 baseline period), and maximum uptake when the average summer Tmin is 17°C (as per UKCP09 2080s high emission scenario). From this relationship for a given mean summer Tmin we estimated the percentage of London's residential floor space that will be air-conditioned and the corresponding energy demand. We then used Equation 1 (McCarthy et al., 2012), with χ = level of heat emissions in GW, to estimate the feedback from energy use on London's UHI.

The method outlined above facilitates a more considered analysis of the relationship between temperature and air-conditioning uptake in the context of a changing climate and London's UHI: as temperatures rise the uptake of air-conditioning will likely increase, which will in turn increase energy use during summer and exacerbate the UHI. For a given level of air-conditioning uptake we estimated the UHI increase, the subsequent additional air-conditioning uptake, and iterated until a stable level of air-conditioning uptake was established. The impacts of varying air-conditioning access for the least and most vulnerable residents in London were explored through scenarios.

4.2.2.3 Upgraded building stock

Built form, the level of building fabric retrofit, orientation, and the availability and performance of ventilation and other building characteristics may influence the risk of buildings overheating (Mavrogianni et al., 2012). While occupant behaviour (Mavrogianni et al., 2014) and external climate (Oikonomou et al., 2012, Taylor et al., 2015b) can influence the relative overheating risk within building types. The effects of built form and dwelling characteristics appear to have a greater influence on variation in internal temperatures than the location within the UHI (Oikonomou et al., 2012, Taylor et al., 2015b). A number of adaptation actions may be implemented to reduce the overheating risk within London's buildings (Taylor et al., 2015b, Porritt et al., 2012). Previous research has indicated that during a typical hot period in London, roof insulation and window upgrades decreased peak internal temperatures by 1.3°C (Mavrogianni et al., 2012).

Taylor et al. (2015b) undertook thermal performance simulations for 17 London building archetypes across 8 orientations using EnergyPlus (US-DOE, 2013) at an hourly time-step, using weather files for a Central London design summer year. We

further analysed these simulation outputs to estimate the effectiveness of improving the overheating performance of the eight most common building types in London. The difference between external and internal temperatures for each hour when the external temperature was above 24.8°C was calculated. A mean building performance factor (MBF) was calculated for each of the 2016 simulations. Cumulative distribution functions of the MBFs were plotted for each of the eight building types: the minimum, mean and maximum values are shown in Table 4-2.

Future research is planned to update the building physics models to explicitly include a range of specific adaptation actions (Taylor et al., 2015b). For this research however, we considered building level adaptation to mean each building could be renovated or replaced such that its overheating performance would be equivalent to the best performer in its type. We considered a scenario of natural replacement, but because the replacement of UK building stock is low (typically 1% per year) only around 20% of buildings will be replaced between now and the 2050s (ASC, 2015, GLA, 2015a). In addition we considered renovation scenarios in which 50% and 100% of buildings are upgraded.

Table 4-2 Mean Building Factors provide an estimate of the effectiveness of buildings in moderating internal temperatures relative to external temperatures during hot weather for London's eight most common residential building types (°C)

	Minimum MBF	Mean MBF	Maximum MBF
Bungalow	0.55	1.74	3.13
Converted flat	-1.57	0.86	4.03
Detached	-2.02	-1.12	-0.19
End terrace	-1.23	0.38	3.02
High-rise purpose-built flats	-4.75	-2.14	7.75
Low-rise purpose-built flats	-2.96	-0.58	3.48
Mid-terrace	-1.78	-0.18	2.48
Semi-Detached	-1.78	-0.31	1.67

4.2.3 *Adaptation portfolios*

Adopting a portfolio approach provides the flexibility to cope with various possible future conditions and can help compensate for the inevitable weaknesses or vulnerabilities of any one action. Portfolios are drawn from the adaptation canvas and may be selected: in consultation with stakeholders; within a modelling environment to respond to threshold levels of climate-risk; through expert judgement; or a combination thereof (Haasnoot et al., 2013). Portfolios should be of interest to stakeholders and include adaptive actions that may be appropriate under a range of potential futures. Due to the exploratory nature of this research we specified 12 portfolios using a combination of urban greening, air-conditioning and building level adaptation actions.

4.2.4 *Adaptation pathways*

Pathways may also be scheduled through stakeholder consultation, expert judgement or within a modelling environment to respond to threshold levels of climate-risk (Haasnoot et al., 2013, Reeder and Ranger, 2011). Pathways were selected to represent a range of adaptive strategies that may be informative to stakeholders in London. The actions in the portfolios were scheduled to explore feasible timescales over which adaptation options could be implemented. For the purposes of this research one pathway was developed for each portfolio as described in Table 4-3. The values in Table 4-3 reflect the scenario results for urban greening, air-conditioning, and upgraded building stock generated following the methods outlined above.

Table 4-3 Scheduling by decade portfolios of distributed heat risk reduction actions for the 12 adaptation pathways appraised in this chapter.

Pathway	Description	Portfolio	Percentage change			
			Baseline	2030s	2050s	2080s
1	Urban greening – green roof saturation	Increase green roof area	0	41	82	82
		Building upgrade	-	-	-	-
		Increase green space area	-	-	-	-
		Residential air-conditioning	-	-	-	-
2	Urban greening - 25% increase in green space	Increase green roof area	0	25	50	50
		Building upgrade	-	-	-	-
		Increase green space area	0	13	25	25
		Residential air-conditioning	-	-	-	-
3	Greening – 50% increase in green space	Increase green roof area	0	45	90	-
		Building upgrade	-	-	-	-
		Increase green space area	0	4	35	50
		Residential air-conditioning	-	-	-	-
4	Air conditioning - temperature driven uptake (random distribution)	Increase green roof area	-	-	-	-
		Building upgrade	-	-	-	-
		Increase green space area	-	-	-	-
		Residential air-conditioning	3	18	40	62
5	Air conditioning – 50% uptake (most vulnerable prioritised)	Increase green roof area	-	-	-	-
		Building upgrade	-	-	-	-
		Increase green space area	-	-	-	-
		Residential air-conditioning	3	9	36	50
6	Air conditioning – 100% uptake (random distribution)	Increase green roof area	-	-	-	-
		Building upgrade	-	-	-	-
		Increase green space area	-	-	-	-
		Residential air-conditioning	3	15	67	100
7	Building stock upgrades – replacement rates	Increase green roof area	-	-	-	-
		Building upgrade	0	12	23	40
		Increase green space area	-	-	-	-
		Residential air-conditioning	-	-	-	-
8	Building upgrade – 50 % stock	Increase green roof area	-	-	-	-
		Building upgrade	0	25	50	50
		Increase green space area	-	-	-	-
		Residential air-conditioning	-	-	-	-
9	Building upgrade – 100 % stock	Increase green roof area	-	-	-	-
		Building upgrade	0	15	67	100
		Increase green space area	-	-	-	-
		Residential air-conditioning	-	-	-	-
10	Greening & Building	Increase green roof area	0	25	50	50
		Building upgrade	0	25	50	50
		Increase green space area	0	13	25	25
		Residential air-conditioning	-	-	-	-

Pathway	Description	Portfolio	Percentage change			
			Baseline	2030s	2050s	2080s
11	Greening & Building	Increase green roof area	0	7	63	90
		Building upgrade	0	15	67	100
		Increase green space area	0	4	35	50
		Residential air-conditioning	-	-	-	-
12	Air-conditioning, Urbanisation (least vulnerable install air-conditioning)	Increase green roof area	-	-	-	-
		Building upgrade	-	-	-	-
		Increase green space area	0	-5	-16	-25
		Residential air-conditioning	3	9	36	50

4.2.5 Pathway appraisal

The appraisal of sequential adaptation pathways demonstrates to decision-makers how climate-risk may (or may not) be managed. We used an urban climate change impact assessment model, which built on the impact assessment framework described in Jenkins et al. (2014b), to appraise the effectiveness of adaptation pathways in managing heat-risk.

4.2.5.1 Modelling framework

The model incorporates probabilistic projections of daily maximum (Tmax) and minimum (Tmin) temperatures, at a 5km² resolution, from a spatial version of the UKCP09 WG (Kilsby et al., 2011). This enables a probabilistic analysis of heat events, as well as providing an assessment of underlying climate model uncertainties (Jenkins et al., 2014b). The WG is conditioned upon a large ensemble of future climate conditions obtained from the UKCP09 climate projections (Murphy et al., 2009). Daily time-series data for 30-year stationary sequences are taken from the WG for each grid cell in the research area. These series are generated 100 times each, with each run based on a different randomly sampled vector of change factors, to allow probabilistic analysis. Data was generated for a baseline period of 1960–1990 and then for three 30-

year time periods centred on the 2030s, 2050s and 2080s. The pathway appraisal was undertaken using the UKCP09 medium emissions scenario, which corresponds to the A1B Special Report on Emissions Scenario (SRES) (Murphy et al., 2009). The SRES A1B is equivalent to a median global mean temperature increase of approximately 2.75°C by the 2080–2100 period (compared with a 1980–1999 baseline); it is positioned between Representative Concentration Pathways 6.0 and 8.5 (IPCC, 2013).

A population projection based on long-term growth trends and the 2011 census was used up until 2040 (GLA, 2014a). From 2040–2100 long-term baseline projections (Zuo et al., 2014), scaled to account for the greater than projected growth in London between the 2003 and 2011 censuses, were used. This represents a population increase from 8.6 million in 2015 to 10.0 million in the 2030s, 10.9 million in the 2050s and 11.0 million in the 2080s. For each London borough,⁴ the data was disaggregated to a ward scale based on the present day population distribution.

Housing stock in London grew less than 1% annually in the 2000s, far slower than population over the same period (GLA, 2015a). Given London's relatively slow turnover of building stock, the proportion of property types was assumed to remain constant in this analysis. Estimates of the number of residents living in each of the eight most common building types in London, in each ward, were made based on census data (ONS, 2013), with further dwelling data derived from the AddressBase Plus database (OS, 2015a) and the UKBuildings database (GG, 2013).

⁴ There are 32 boroughs, in addition to the City of London, in Greater London, each of which is equivalent to a local government district; which are divided into 628 wards.

Climate hazard was assessed in terms of the exceedance of temperature thresholds. Adaptation actions were integrated into the risk assessment framework, their inclusion modifying the probability that relevant thresholds may be exceeded. For example, urban greening and waste heat from air-conditioning modify the UHI, air-conditioning affects the number of individuals exposed to overheating, and building-level adaptations alter the relationship between internal and external T_{max} .

4.2.5.2 Risk metrics

Heat-risk metrics should provide evidence as to the changing nature of heat-risk, to monitor climate impacts and prioritise adaptation actions. Multiple metrics will be required to understand heat-risk in complex urban systems. Metrics that reflect changes in multiple drivers of risk – including climate change, the UHI, social vulnerability and adaptation action – are more valuable to decision makers than those that only reflect the changing climate hazard. We adopted mortality, residential overheating and risk of exceeding target frequency for residential overheating events for this research.

It is well established that high temperatures are associated with increased mortality (Vardoulakis et al., 2014, Hajat et al., 2014, Armstrong et al., 2011, Gasparrini et al., 2015), and mortality has been used as a metric in a number of heat-risk studies (Taylor et al., 2015b, Stone et al., 2014, Jenkins et al., 2014b). Mortality is of interest to a broad range of decision makers, but especially those in the health sector (Zaidi and Pelling, 2015).

The baseline background daily mortality rate was identified from data on annual mortality rates at the ward level (Zuo et al., 2014), and summer weighted daily mortality rates for each future time period were updated from Jenkins et al. (2014b). Heat-related mortality was calculated based on epidemiological relationships between

mortality and temperature: a mean daily temperature threshold of 20°C above which heat-related mortality increases on average by 3.1% per 1°C rise was adopted (Jenkins et al., 2014b). Annual average heat-related mortality was calculated for each ward and across Greater London.

It should be noted that, as mortality estimates are based on historic data, it remains to be seen whether these relationships will hold for the future given potential acclimatisation as well as infrastructure, technological and institutional governance changes (Zaidi and Pelling, 2015, Armstrong et al., 2011). Given the importance of mortality estimates to public health management, it is a useful metric to use in adaptation planning, however it should be used with an understanding of its limitations, and as part of a portfolio of indicators.

The level of residential overheating is an important and useful metric for heat-risk as indoor temperature extremes are of more direct consequence to heat vulnerability than the occurrence of climate based heatwaves, and are mediated by individual building use and design (Zaidi and Pelling, 2015, Mavrogianni et al., 2012, Mavrogianni et al., 2014).

There is currently no universal definition of residential overheating. An adaptive comfort based approach (CIBSE, 2013) that seeks to account for acclimatisation has been developed for the UK (ZCH, 2015). However, the most commonly adopted overheating criteria are based on CIBSE's Guide A (2006), which specifies that above an internal temperature of 28°C people will feel discomfort in living spaces. Based on this internal temperature threshold, in combination with the building performance factors described in 4.2.2.3, we identified building specific external temperature

thresholds above which residential discomfort may occur in each building type, as per Table 4-4.

Table 4-4 External overheating thresholds for eight London building types. When these temperature thresholds are exceeded residents experience discomfort from overheating. Building scale adaptation has the potential to increase these thresholds.

Building type	Existing average external Tmax threshold	Adapted average external Tmax threshold
Converted flat	27.1°C	27.7°C
Detached	29.1°C	29.6°C
Bungalow	26.3°C	26.7°C
High-rise purpose-built flats	30.1°C	30.9°C
Low-rise purpose-built flats	28.3°C	28.8°C
Semi-Detached	28.3°C	28.8°C
End terrace	27.6°C	28.1°C
Mid-terrace	28.2°C	28.8°C

Whilst this approach simplifies the processes that relate external to internal temperatures at an individual building level, they do provide an indication of the overheating risks related to different residential building types and how such risks could change in the future (Jenkins et al., 2014b).

We estimated the number of people subject to residential overheating based on the daily Tmax of the spatial WG simulation in each ward, the number of people living in each building type, and relevant temperature thresholds for each building type. We then calculated the percentage of total residents at risk from thermal discomfort per daily event, as an indicator of the scale of overheating risk.

Heatwave definitions range from those based on the characteristics of a climate hazard, as adopted in London, to those based on the level of impact (Zaidi and Pelling, 2015), such as mortality or economic losses. We propose that as the level of sophistication with which heat-risk is managed increases, similar to what has occurred for other natural hazards such as flooding (Beven and Hall, 2014) and drought (Hall et al., 2012d,

Brown et al., 2015), there is an emerging role for probabilistic impact-based heatwave definitions. As a demonstration we proposed three potential heatwave levels based on increasing numbers of people exposed to residential overheating, described in Table 4-5.

Table 4-5 Demonstration of residential overheating heatwave levels, based on the percentage of residents in each ward that experience overheating for 5 or more consecutive days.

Heatwave level	Threshold level	Heatwave length
	Percentage of residents experiencing overheating	Consecutive Days
1	10	5
2	25	5
3	50	5

Within the impact assessment model, the number of people in each ward exposed to residential overheating each day was calculated across eight building types. A threshold detector was applied to identify when the percentage of residents exposed to overheating in each ward exceeded the heatwave threshold level. Then the number of consecutive days that the threshold level is exceeded was calculated to identify the number of five-day heatwaves. The annual frequency of level 1–3 heatwave events was calculated based on a 30-year model run and the p10, p50 and p90 values estimated based on 100 model runs.

4.3 RESULTS

The spatial coherence of the WG and impact assessment approach allows data to be aggregated across London for each daily heat event and assessed in probabilistic terms. Results are first presented for individual adaptation categories (Section 4.3.1) and then in combination as part of our adaptation pathways (Section 4.3.2). Unless specified

otherwise, the results presented are for the median values (50th percentile) under the UKCP09 medium greenhouse gas emissions scenario.

In the 2080s there are estimated to be more than 950 additional heat-related deaths attributed to increasing temperatures and the number of residents exposed to residential overheating is estimated to increase from 18% to 92%. The probability that more than 25% of London's residents will be exposed to 5 consecutive days of overheating is estimated to increase from less than 0.1 in the baseline to more than 2.5 by the 2080s, as per Figure 4-3. This highlights the need to consider a broad range of future adaptation actions, portfolios and pathways for city-scale urban adaptation in London. Our results show the effectiveness of individual adaptation actions and present the appraisal of our demonstration adaptation pathways.

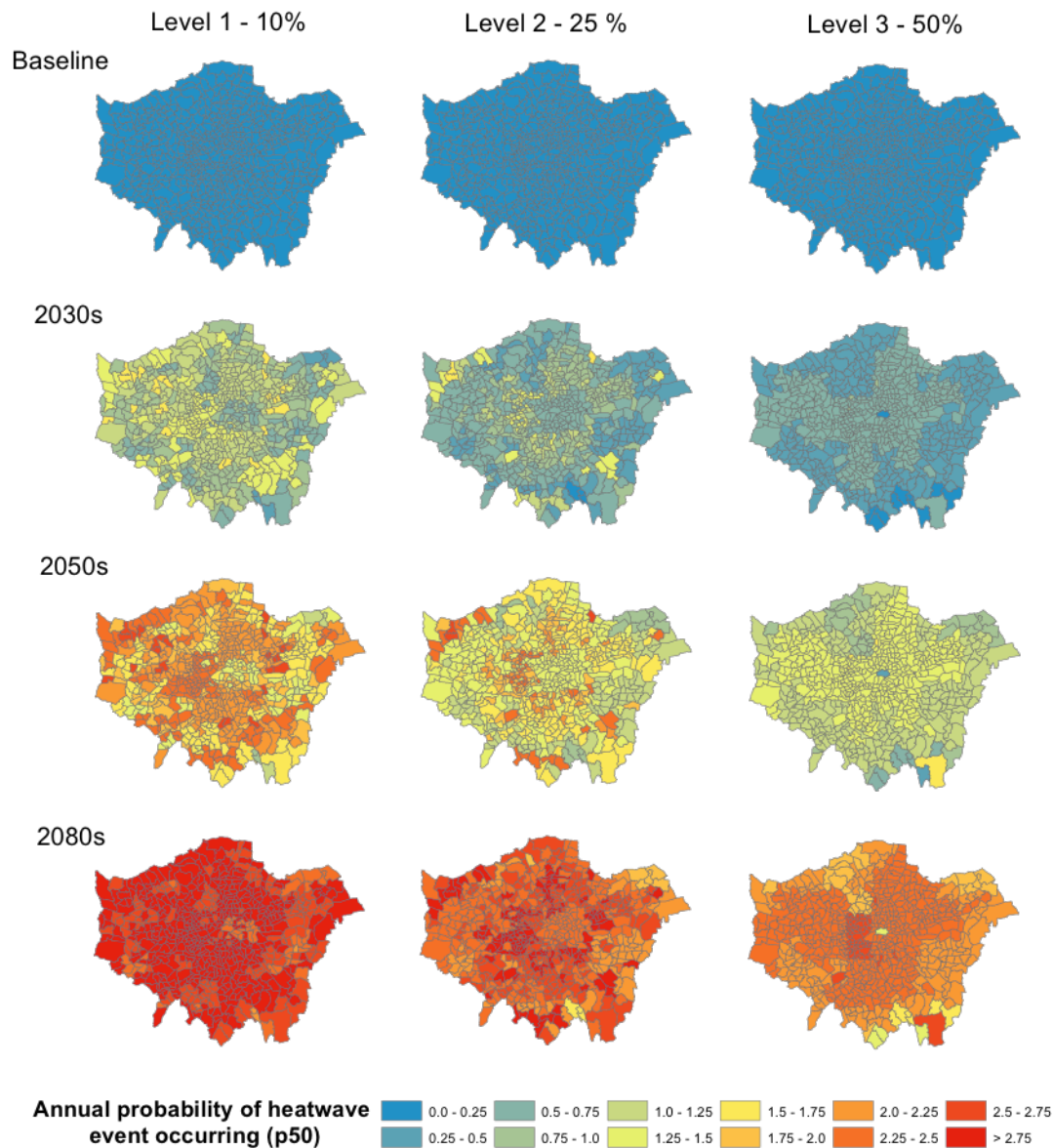


Figure 4-3 Residential overheating risk by ward for each of the three demonstration heatwave levels during the baseline, 2030s, 2050s and 2080s assuming that no adaptation actions are implemented

4.3.1 Adaptation action appraisal

4.3.1.1 Urban greening

City-scale urban greening has the potential to decrease the UHI impact, as Table 4-6 shows. Increasing London's urban green space by 50% is projected to reduce future summer Tmax by 0.28°C. In the 2080s this corresponds to 49 less heat-related deaths each year compared to a no-adaptation scenario, as per Figure 4-4. Alternatively, decreasing London's green space by 25% by the 2080s is projected to increase summer

Tmax by 0.17°C, which corresponds to 26 more heat-related deaths per year compared to a scenario where existing levels of urban greening are maintained. The difference between increasing and decreasing levels of urban greening by 25% is estimated to be 54 deaths annually in the 2050s and 60 in the 2080s. When considering the number of heatwaves (Levels1–3) and the potential impact of increased greening, we observe heat-risk increasing as green space decreases, as per Figure 4-5.

Table 4-6 Impact of changes in vegetation cover on summer Tmax and Tmin for scenarios described in Table 4-1

Green space type	Existing estimated area	Scenario	Scenario estimated area	Change in summer Tmin	Change in summer Tmax
Green roofs	< 5km ²	Estimated green roof saturation	83km ²	-0.016°C	-0.068°C
Parks/gardens	760km ²	25% increase in urban green space	950km ²	-0.038°C	-0.149°C
Parks/gardens	760km ²	25% decrease in urban green space	570km ²	0.037°C	0.172°C
Parks/gardens	760km ²	50% increase in urban green space	950km ²	-0.077°C	-0.275°C
Parks/gardens	760km ²	50% decrease in urban green space	1140km ²	0.073°C	0.368°C

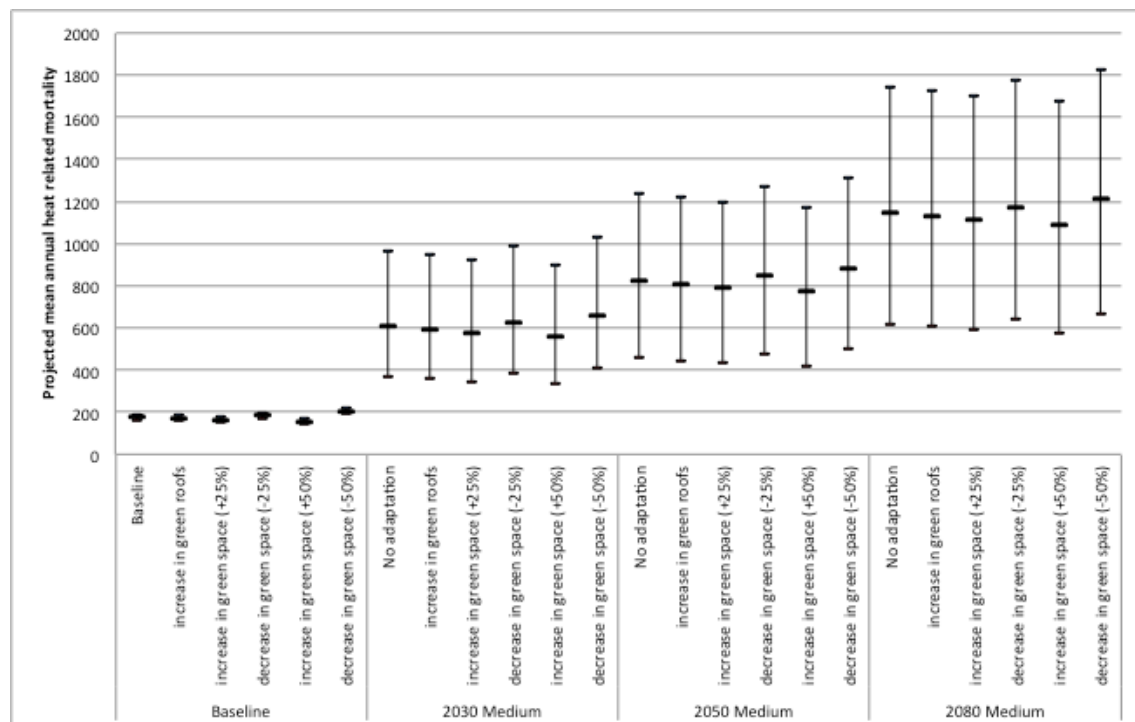


Figure 4-4 Estimated annual heat-related mortalities under the urban greening scenarios described in Table 4-1 (p10 and p90 are lower and upper bounds)

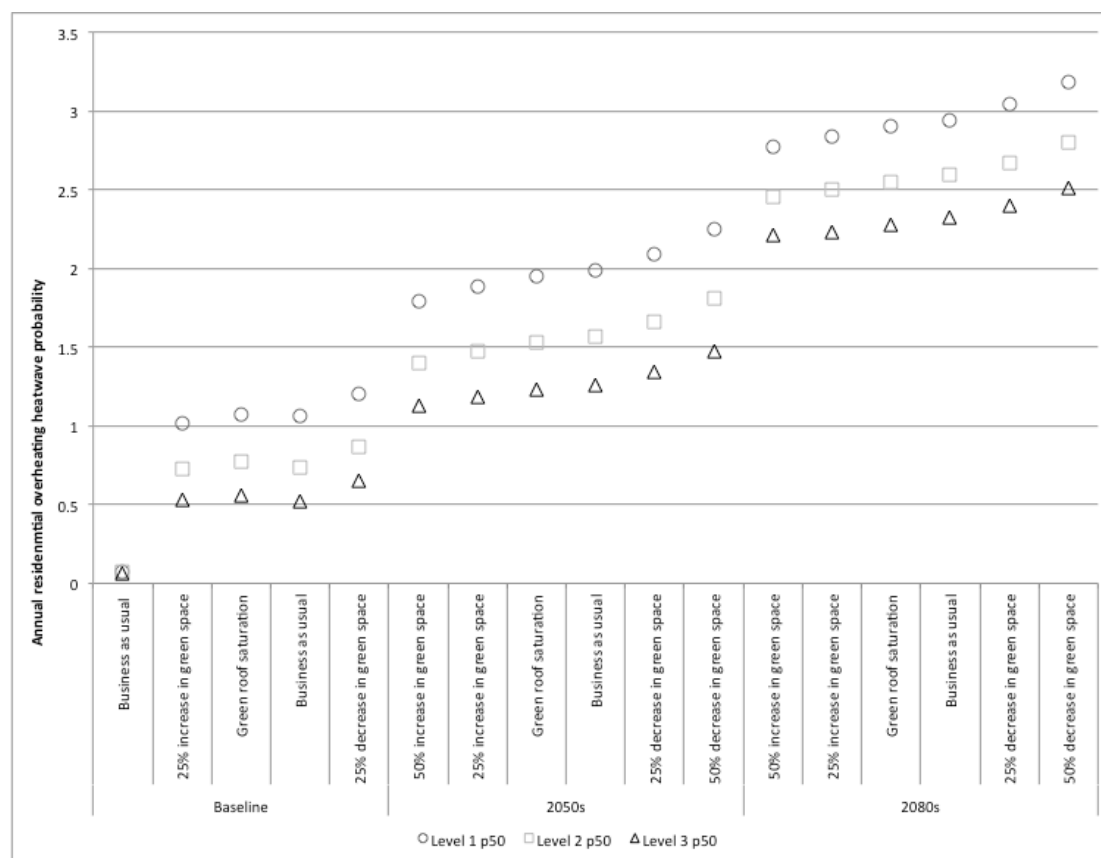


Figure 4-5 Median values for London's average annual frequency of Level 1–3 heatwaves (as described in Table 4-5) for the urban greening scenarios described in Table 4-1

It is noted that these results focus on the impacts of green infrastructure on the UHI and do not reflect localised benefits such as shading of buildings (Rogers et al., 2012, Doick and Hutchings, 2013), or the enhanced insulation provided by green roofs (Virk et al., 2014). Nor do they seek to quantify benefits of urban greening such as storm water attenuation (Stovin et al., 2012) or improved amenity and biodiversity value (Gill et al., 2007, Demuzere et al., 2014).

4.3.1.2 Air-conditioning

Our estimate of the total energy demand for London assumes that a cooling unit with an energy demand of 1.7kW (at 30°C) is used to cool an average size room in London (DCLG, 2014). In a scenario where 100% of the 3.4 million residential dwellings in London (ONS, 2013) were cooled, an additional 13.2GW of peak demand would be

generated. Day and Opara (2012) estimated this demand to be 11.5GW, given this result is within 20%, it is considered a reasonable estimate. Differences may be attributed to different methods or assumptions regarding the future mix of cooling technologies, energy efficiency ratios and potential growth in residential floor space.

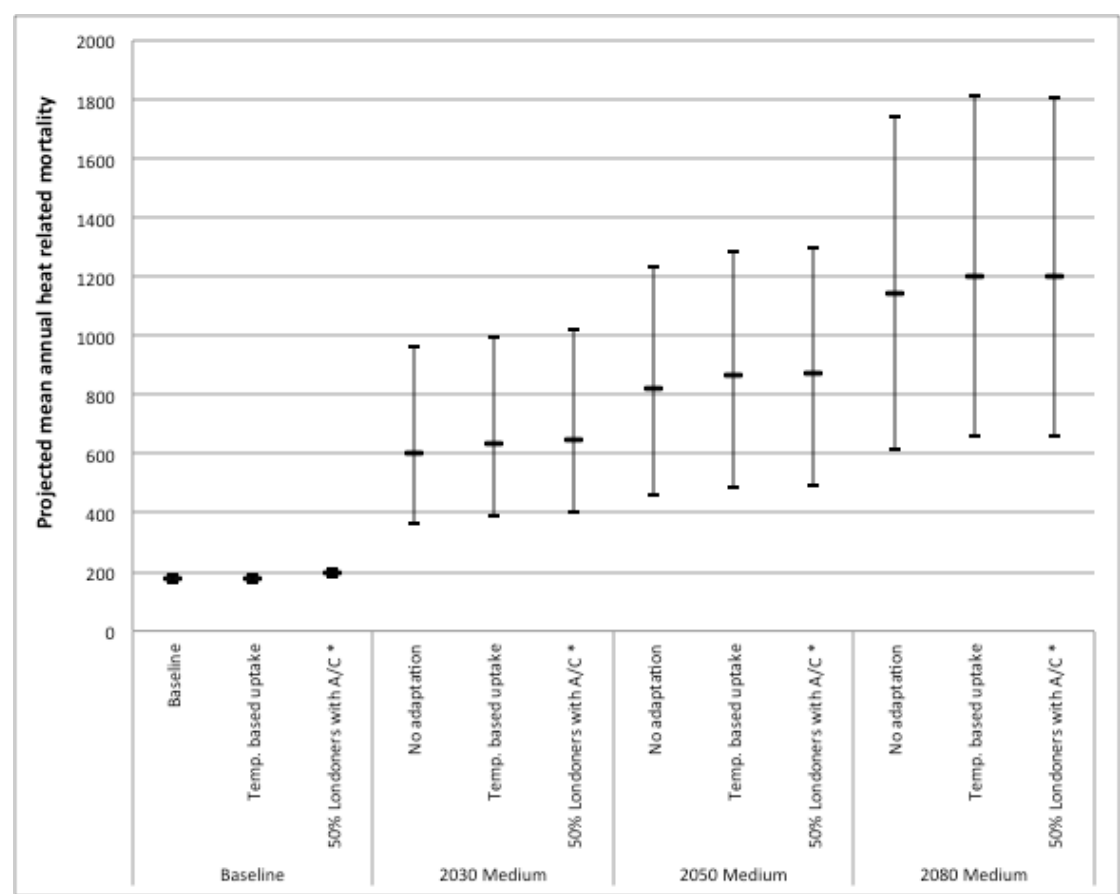
Table 4-7 describes the estimated uptake rates for air-conditioning in response to increasing temperatures due to climate change. Whilst London's current uptake rates for residential air-conditioning are low, the results highlight that if uptake is driven in a similar manner to US cities, then under a medium emissions climate change scenario 40% of London's residential floor space may be air-conditioned by the 2050s, increasing to more than 60% by the 2080s. Such a scenario would have significant implications for mortality and residential overheating, especially from an equity perspective as those who are most vulnerable to an increasing UHI are often of low economic status (Wolf and McGregor, 2013) and are likely to be least able to afford residential air-conditioning. It would also have significant implications for London's energy generation and greenhouse-gas emissions (Day et al., 2009).

Table 4-7 Projected air-conditioning uptake based on projected increases in overnight temperatures in the 2030s, 2050s and 2080s and the corresponding increase in maximum and minimum temperatures resulting from the air-conditioners' contribution to the Urban Heat Island

Climate scenario		UKCP09 P50 Tmin	London air- conditioner saturation	UHI change in summer Tmin	UHI change in summer Tmax.
Time	Emissions	$\Delta T_{min} - JJA$	Percentage of residents	$\Delta T_{min} - JJA$	$\Delta T_{max} - JJA$
Baseline	N/A	0.0	0.7	0.01	0.00
2030	Medium	2.0	18	0.18	0.04
2050	Medium	2.7	40	0.23	0.08
2080	Medium	3.9	62	0.25	0.13

In a scenario where 50% of Londoners utilise air-conditioning, summer Tmax and Tmin are estimated to increase by 0.11°C and 0.25°C respectively due to the waste

heat’s impact on the UHI. As an upper bound under this scenario, if the residents who utilise air-conditioning are the least vulnerable to heat-risk (these are typically healthy and wealthy individuals (Wolf and McGregor, 2013)), it is estimated that there will be 55 additional heat-related deaths per year in the 2080s compared to a scenario with no change to the UHI, as per Figure 4-6.



* Assumes air-conditioning is utilised by the least vulnerable and additional impact of increases in the UHI affects the most vulnerable.

Figure 4-6 Mean annual heat-related mortality under three scenarios of future residential air-conditioning uptake (p10 and p90 are lower and upper bounds, respectively)

In London in the 2050s the median value for the average annual probability that 25% of residents will experience 5 consecutive days of residential overheating is 1.6 assuming there is no adaptation. If it is assumed that the least vulnerable 50% of London’s residents install air-conditioning it increases to 2.8 due to the impact of air-conditioning on the UHI, which will affect the most vulnerable residents. However, if the most

vulnerable 50% of the population have access to residential air-conditioning it decreases to 1.3, due to the internal cooling provided by air-conditioning. Levels of residential overheating risk at the ward scale, under these three scenarios, are mapped in Figure 4-7.

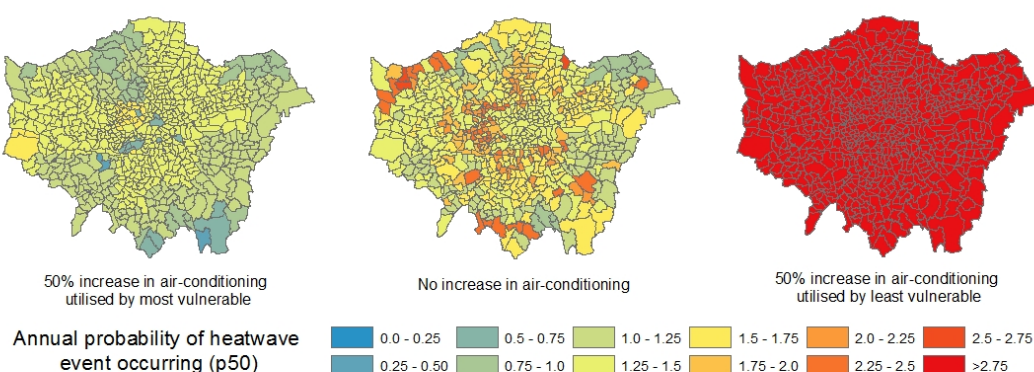


Figure 4-7 Annual probability that 25% of residents will experience 5 consecutive days of residential overheating (2050s medium emissions scenario p50) for three air-conditioning scenarios

4.3.1.3 Upgraded building stock

Our results show that upgrading London's building stock so every building's overheating performance is equivalent to the current best performing archetype for a given building type will be insufficient to maintain existing levels of overheating risk in the 2030s and beyond. However, it would reduce projected residential overheating risk more than increasing urban greening by 50%. Figure 4-8 outlines future overheating risk results per ward for a Level 1 Heatwave, Table B-1 in the Appendix outlines the changes in overheating risk with and without building level adaptation, averaged across London.

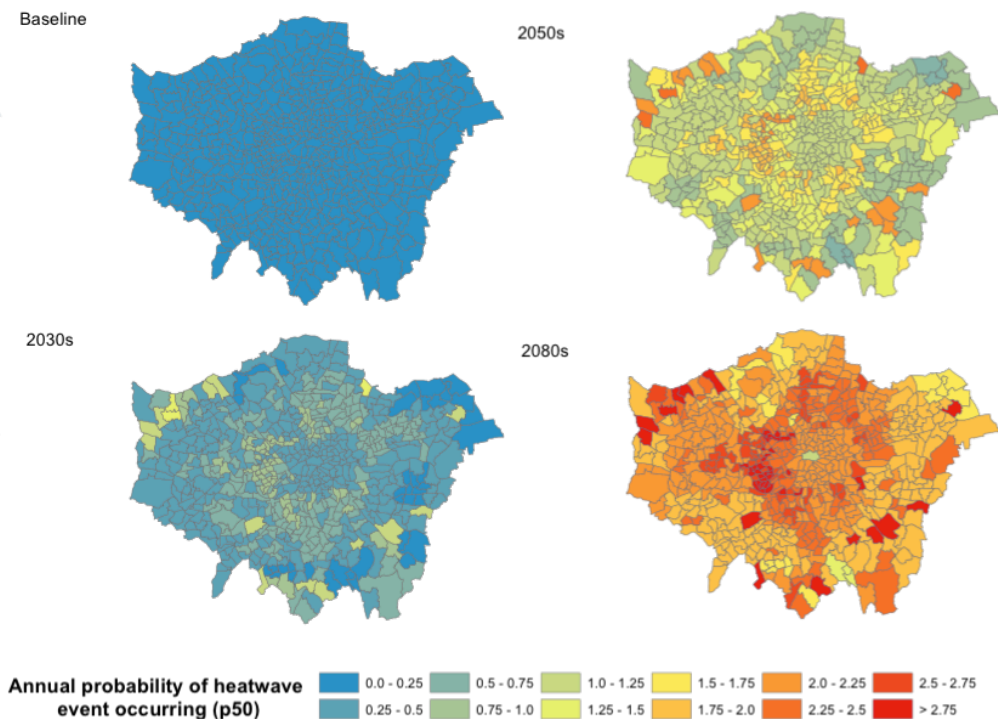


Figure 4-8 Impact of upgrading 100% of the building stock on the annual probability that 10% of residents will experience 5 consecutive days of residential overheating (Level 1 heatwave) (medium emissions scenario p50)

4.3.2 Adaptation pathways appraisal

Heat-risk was calculated at the ward level for the 2030s, 2050s and 2080s for each of the 12 demonstration pathways. Figure 4-9 outlines the average projected Level 2 heat-risk across London with results for additional metrics included in the supplementary material. Urban greening alone (Pathways 1–3) has a positive impact on reducing heat-risk compared to the no-adaptation scenario, but will not reduce the UHI enough to offset the impacts of climate change even under the extremely optimistic uptake scenario represented in Pathway 3.

Pathways 4, 5 and 6 are scenarios of varying uptake and access to air-conditioning. Pathway 4 assumes that uptake of air-conditioning is evenly distributed and follows the temperature-based uptake described in Table 4-7, which results in lower levels of risk than the no-adaptation scenario but higher levels of risk than the baseline period. Pathway 6 assumes that uptake of air-conditioning is evenly distributed and the uptake

follows a logistic uptake curve peaking at 100% in 2100. This results in similar levels of risk to Pathway 4 in the 2030s and 2050s but it is effectively reduced to 0 once 100% air-conditioning uptake is achieved. Pathway 5 assumes air-conditioning is utilised by the most vulnerable; this pathway has slightly lower levels of risk despite also having lower levels of air-conditioning uptake, compared with Pathway 4. In Pathways 4–6 serious concerns would need to be addressed regarding the potential increase in greenhouse gas emissions, the mix and the capacity of London's future energy generation system (Day et al., 2009).

Whilst building-scale adaptation has been demonstrated in modelling studies to deliver adaptation benefits (Porritt et al., 2012, Mavrogianni et al., 2012), it has not at the city scale. As demonstrated in Pathways 7–9, at the city scale this would require improvements in the existing building stock, with thermal performance improving beyond that which is observed in London's existing building stock. This would also require building level retrofits to be undertaken faster than existing stock replacement rates.

Pathways 10 and 11 are optimistic scenarios from an adaptation and mitigation perspective. Pathway 11 would reduce the probability of Level 2 heatwaves by 0.3 in the 2050s and 0.48 in the 2080s, compared to the no-adaptation scenario. However, even following Pathway 11, heat-risk will continue to rise in each future time period compared to the baseline. Pathway 12 demonstrates potential increases in heat-risk from future reduction in levels of urban greening, in addition to increases in air-conditioning uptake by residents not considered vulnerable to heat-risk. This is estimated to increase the annual frequency of a Level 2 heatwave by 1.25 in the 2050s and 0.98 in the 2080s. Pathway 12 brings forward heat-risk by more than 30 years, as shown in Figure 4-9 the level of heat-risk in 2050 exceeds the risk level in Pathways 1–11 in the 2080s.

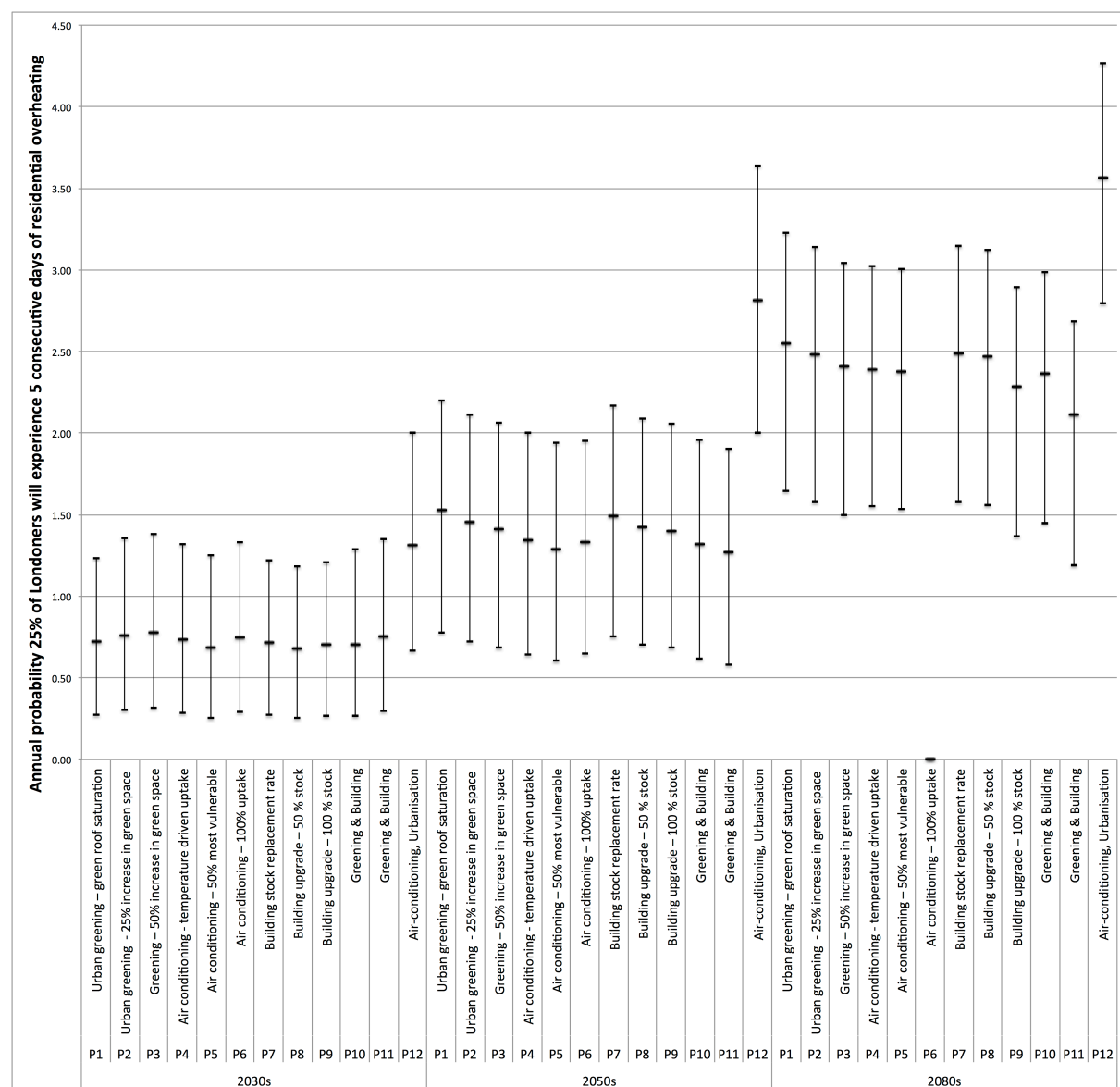
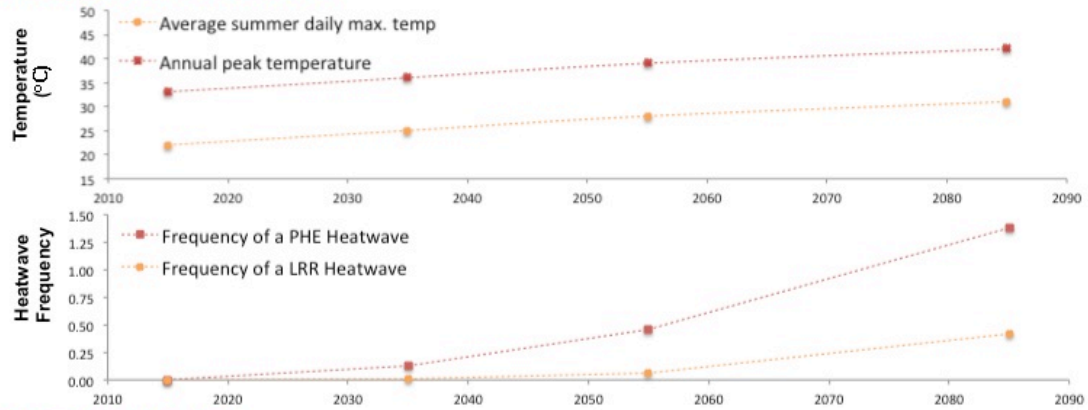


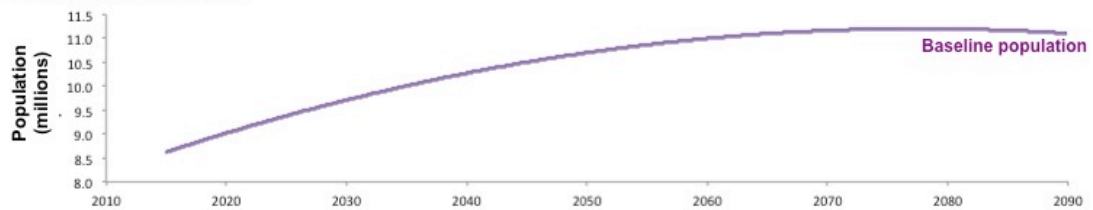
Figure 4-9 Annual probability that 25% of residents will experience 5 consecutive days of residential overheating (Level 2 heatwave as per Table 4-5) for each adaptation pathway described in Table 4-3

Pathways diagrams were developed for the 12 pathways that bring together indicators for four attributes of climate-risk that change through time: (1) indicators of the changing climate hazard; (2) an exposure indicator; (3) a dynamic adaptation pathway; and (4) quantified indicators of climate-risk. The time dimension provides a sense of the temporal scale at which a pathway is applicable, which assists decision makers in visualising the dynamic risk. Figure 4-10 is an example pathway diagram, highlighting Pathway 10.

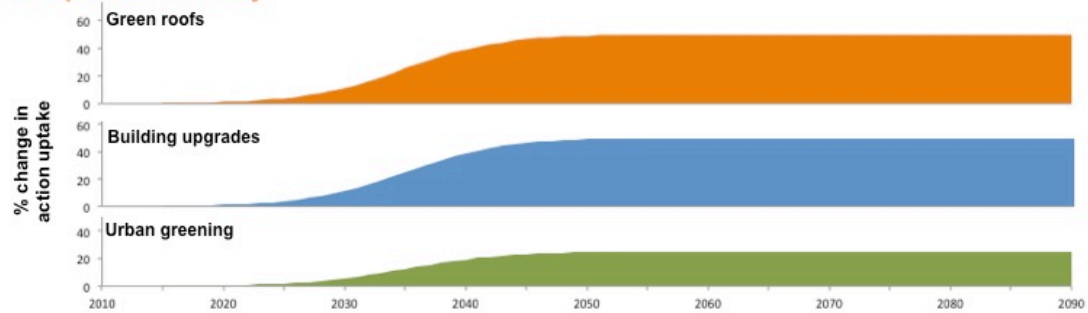
Climate Hazard Indicators



Exposure Indicator



Adaptation Pathway



Risk Projection

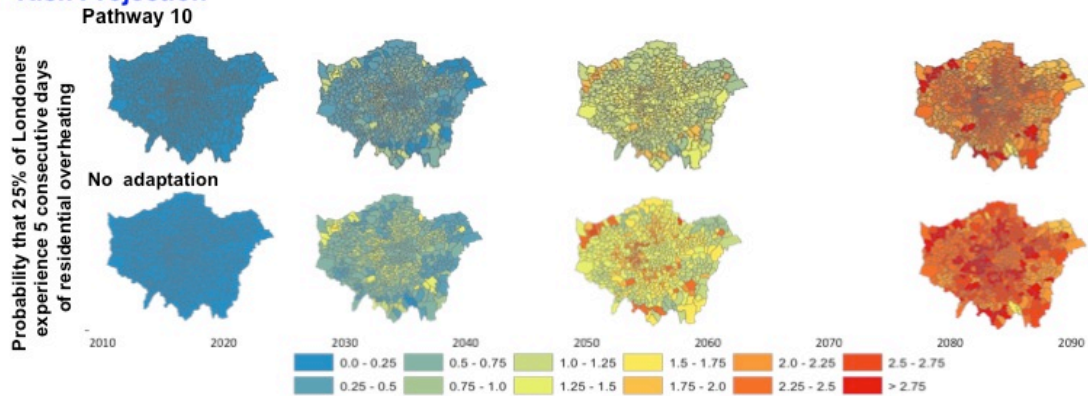


Figure 4-10 Adaptation Pathway Diagram for Pathway 10 that increases the percentage of dwellings with green roofs, upgrades the building stock so it is better adapted to hotter summer temperatures and increase the area of green space. All actions are implemented following a logistic uptake curve with all actions implemented by the 2050s.

4.4 DISCUSSION AND CONCLUSIONS

This research proposes a new approach to manage long-term heat-risk at the city scale through demonstrating an adaptation pathways approach in London. A pathways approach contributes to the development of dynamically robust plans by incorporating flexibility in the scheduling and implementation of actions, and allowing changing levels of risk to inform future decisions.

Considering heat-risk at the city scale requires some simplifying assumptions compared with building or neighbourhood-scale analysis, however it is at the city scale that many critical decisions are made which affect future heat-risk, including land-use planning and building regulations. In London, for example, the GLA have a mandate to manage heat-related climate-risk (HM Government, 2007) but they have limited tools that assist them in quantifying the potential effectiveness of adaptation actions.

Our approach is complementary to approaches developed by Wolf and McGregor (2013) and Taylor et al. (2015b) to understand existing vulnerability and climate-risk. However, a long-term approach provides additional value given the projected future scale of heat-risk and the need for planned adaptation (Jenkins et al., 2014b). Actions that alter the fabric of a city are typically challenging and slow to implement but they have long-term implications (Hallegatte and Corfee-Morlot, 2010). A long-term plan reduces the likelihood of mal-adaptation and undesirable lock-in, creates awareness of the dynamic nature of the climate system, and builds the political and business case for integrating flexibility into planning (Ranger et al., 2013).

Whilst building type has been found to have a greater influence on existing heat-risk than the UHI (Taylor et al., 2015b, Oikonomou et al., 2012, Mavrogianni et al., 2011), there has been limited research that appraises the effectiveness of building-level

adaptation compared with urban greening or air-conditioning at the city scale under future climate scenarios. This research addresses the need for climate change risk assessment to incorporate the appraisal of the effectiveness of adaptation actions. This has allowed us to better understand the potential effectiveness of a range of portfolios of actions that may or may not be proportionate to the scale of the adaptation challenge. The results have highlighted the limitations of adaptation strategies that focus solely on urban greening or building-level adaptation that does not improve beyond the best performing buildings within London's existing building stock. We have demonstrated the impact of increasing heat emissions from air-conditioning on the UHI and the possible negative consequences.

This research highlights the scale of the heat-risk adaptation challenge facing London and demonstrates the potential of a pathways approach, using new and existing indicators of heat-risk. Our results reveal that heat-risk will not be maintained at existing levels by the portfolios of adaptation actions identified, unless supplemented by air-conditioning. However, if Londoners' successfully exhibit physiological acclimatisation and/or behavioural adaptations, the rate of mortality per degree rise in temperature may be lower than reflected through historical mortality response functions (Stone et al., 2014), and residential overheating risk may be lower than that reflected through an absolute overheating limit (CIBSE, 2013).

The development of pathways diagrams has been a key component of the research. They contribute to communicating the potential scale of the challenge and the value in adopting a flexible approach to climate-risk management (Reeder and Ranger, 2011, Kingsborough et al., 2016) that is informed by effective monitoring and evaluation (Kingsborough et al., Submitted). Initial stakeholder feedback found the pathways

diagrams to be a potentially valuable input to long-term planning. However, the application of a risk-based approach to the development of adaptation pathways for heat-risk remains challenging. From an institutional perspective, managing heat-risk is difficult given the limited statutory requirements to manage urban heat-risk beyond heatwave response planning (Zaidi and Pelling, 2015). This further compounds challenges associated with defining tolerable levels of heat-risk and trigger values for adaptation action, as they relate to each metric for urban heat-risk. Identifying indicators that are informative, measurable and relevant to a wide range of stakeholders is also a challenge that needs to be addressed to operationalise a pathways approach.

To further develop adaptation pathways in response to heat-risk in London there is a need to identify adaptation portfolios that are proportionate to the projected future levels of risk. Future portfolios may include additional actions identified in Figure 4-1 including building design actions in combination with an increased range of behavioural responses. Overheating risk metrics may be modified to include additional social and demographic information so that underlying vulnerability is accounted for. This research would be complemented by further stakeholder consultation and potential co-development of pathways. This process could be used to facilitate a dialogue regarding tolerable and acceptable levels of heat-risk and linkages to monitoring and evaluation.

We have appraised adaptation actions and pathways in terms of their effectiveness at reducing mortality and managing residential overheating at the city scale, however we acknowledge that city-level decision makers will need to consider a broader range of criteria including cost-effectiveness, equity, greenhouse gas emissions, socio-political acceptability, flexibility and robustness.

Our integrated modelling approach is beneficial in that it facilitates the consideration of a range of impacts and adaptation options within a single framework. Spatially coherent time-series data allowed us to map and identify high risk wards in each time period, however the framework could be updated to incorporate transient climate change projections (Glenis et al., 2015). The use of transient scenarios would allow decision rules to be incorporated endogenously, based on triggers values.

We utilised the UKCP09 probabilistic climate change projections that reflect the stochastic nature of weather and allow for climate model uncertainty to be explored, however we have only used a single emissions, population growth and land-use change scenario. An increased set of scenarios or robustness testing of assumptions and uncertainties could be used to better understand the robustness of proposed adaptation pathways. Given our results, however, priority should be placed on quantifying the effectiveness (and sensitivity to key assumptions) of an increased set of adaptation actions.

This research has demonstrated an innovative approach to the development of adaptation pathways that respond to projected increases in heat-related mortality and residential overheating. We have quantified how risk varies for a range of adaptation pathways through time with climate change and population growth and we have demonstrated how spatially coherent downscaled probabilistic climate change projections that account for changes in urban land cover and the anthropogenic heat flux can be used to inform adaptation planning to the 2080s.

Heat-risk management will become increasingly important in London and processes to manage trade-offs will need to be established so that necessary actions may be implemented. There is significant potential for a pathways approach to be used in

adaptation planning for heat-risk in cities globally, with the degree of quantification dependent on institutional capacity and data availability. This adaptation pathways approach complements long-term planning for flood (Reeder and Ranger, 2011) and water-supply risk (Kingsborough et al., 2016), and demonstrates an effective framework for informing long-term adaptation planning for heat-risk.

5 **Urban adaptation pathways: demonstration of an integrated approach in London**

5.1 ABSTRACT

The need to adopt an integrated city-scale approach to adaptation planning in complex urban systems has been widely recognised. This paper moves beyond calls for long-term integrated approaches by demonstrating how an integrated assessment framework is used to appraise city-scale adaptation pathways for London that respond to multiple climate risks. We use an integrated assessment framework and approach, which builds on the analysis of adaptation pathways in response to individual climate risks, to capture the co-benefits of adaptation actions.

We demonstrate that increasing green infrastructure reduces future heat and surface water flood risk at the city scale in London. Capturing multiple benefits of green infrastructure strengthens the case for these flexible, distributed adaptation actions relative to the centralised capital-intensive interventions that are perceived to be low risk for decision makers but have the potential for high levels of regret.

This research contributes to the evidence base needed to justify long-term planning and realise the benefits of climate risk reduction through the implementation of flexible integrated urban adaptation plans. It is an initial but significant step towards more

integrated urban adaptation that better accounts for the many interdependencies in urban systems.

5.2 INTRODUCTION

Climate resilience is increasingly an attribute of competitive global cities (Bulla et al., 2014, Georgeson et al., 2016). The high density of people, assets and infrastructure in cities make them vulnerable to climate risks (Dawson, 2007, Hunt and Watkiss, 2010, Rosenzweig et al., 2015, Hall et al., 2009). Our understanding of vulnerability and risk, however, is often imperfect as it is affected by social, institutional and physical uncertainties, and because urban systems are complex and dynamic (Brown et al., 2011a, Grove, 2009).

It is the cities that are most responsive to change that will continue to prosper (Dawson, 2007), which requires governance structures and decision-making approaches that promote flexible and/or robust adaptation action (Solecki and Rosenzweig, 2014).

London is a longstanding city of global importance, and its ability to maintain its pre-eminence relies on it being an efficient and low risk place to do business (London Assembly Economy Committee, 2015). Climate risks – from flooding, overheating, water scarcity, and supply chain exposure – are, however, increasing. How London responds to these changes and adapts to the risks posed will be an important example, both nationally and globally. Adaptation in dense urban areas, like London, will involve sustained effort, considerable investment and difficult choices to be made. While the Mayor of London has identified anticipatory adaptation as a cost effective strategy to increase London's long-term resilience (Nickson et al., 2011), the allocation

of scarce resources to adaptation requires evidence to justify the benefits of climate risk reduction.

Given the many uncertainties associated with climate change mitigation, city-level governments increasingly wish to better understand the potential for adaptation to contribute to managing climate risk (Rosenzweig et al., 2015). Climate risk is a function of both the probability and consequence of the hydro-meteorological hazards and the vulnerability and exposure of populations and assets (IPCC, 2012). The exploration of adaptation scenarios provides a method for decision makers to consider the interaction between climate risk and adaptation actions (Vervoort et al., 2014). To quantify the benefits of adaptation action, there is a need for risk assessment methods to model adaptation effectiveness. This will allow for risk assessments to more readily inform adaptation planning and action (Bulkeley and Castán Broto, 2013, Rosenzweig et al., 2015, Aerts and Botzen, 2014, Reckien et al., 2015, Georgeson et al., 2016).

Urban adaptation actions may affect multiple climate risks, and the full range of potential benefits and/or costs are rarely captured in existing appraisal mechanisms (Dawson, 2015, Demuzere et al., 2014, Gill et al., 2007, Kirshen et al., 2007, McEvoy et al., 2006, Solecki et al., 2015, Vigui and Hallegatte, 2012, Walsh et al., 2011). The majority of cities that have completed climate change risk assessments and/or developed adaptation plans have focused on individual sectors or hazards, despite the literature emphasising the importance of integrated urban adaptation planning (Dawson, 2015, NYCPCC, 2015, Rosenzweig et al., 2015, Dawson, 2007). Failure of planning to adequately address the interdependencies across sectors and hazards may lead to inefficient adaptation and/or maladaptation (Dawson, 2015). Without considered decision analysis to demonstrate how such interdependencies may alter the

prioritisation of investment in adaptation, city-level adaptation planning is unlikely to move beyond the status quo (Masson et al., 2014). A novel contribution of this chapter is the demonstration of integrated pathways appraisal using a single coherent framework.

Due to the long lifetimes of urban infrastructure, and path dependency of planning decisions, urban adaptation must also consider long-term planning horizons (Corfee-Morlot et al., 2010, Hallegatte, 2009). There is a need to demonstrate innovative appraisal methodologies that can account for interdependencies, reveal the differences between adaptation policy alternatives, and that are compatible with long-term adaptation planning. Developing effective long-term plans can reduce the likelihood of mal-adaptation and lock-in, create awareness of the dynamic nature of urban systems, and build the political and business case for integrating flexibility into urban adaptation planning (Ranger et al., 2013).

An adaptation pathways approach is recognised as an approach that can contribute to the development of strategic long-term city-scale adaptation planning under conditions of deep uncertainty (Haasnoot et al., 2013, Walker et al., 2013). By sequencing the implementation of actions over time, the system adapts to changing social, environmental and economic conditions, and options remain available to respond to a range of plausible future conditions (Haasnoot et al., 2013, Ranger et al., 2013). The development of adaptation pathways can assist in facilitating stakeholder consideration of acceptable risk thresholds and the implications for future investments in adaptation (Haasnoot et al., 2013). Monitoring of decision-relevant variables is an important component of implementing a pathways approach (Yohe and Leichenko, 2010). This

establishes a linkage between risk assessment and adaptation action that is absent in many adaptation interventions.

A pathways approach was first applied in the Thames Estuary Project (TE2100), which developed a plan for London's estuarine flood risk management to the year 2100 (Ranger et al., 2010b), and has since gathered interest from stakeholders responsible for managing London's climate risks because of the explicit consideration of the timing, scale and effectiveness of adaptation actions (LEC, 2015, London Assembly Economy Committee, 2015). The potential for a pathways approach to contribute to London's long-term adaptation planning beyond TE2100 has been recognised by the London Assembly (LEC, 2015) and the Mayor (2015). Given the interest from institutional stakeholders, the need to address long-term climate risk, and the large body of adaptation research from which to draw upon, London presents an ideal case study city to demonstrate innovative approaches to the development and appraisal of integrated urban adaptation pathways.

This paper presents a framework for the assessment of multiple climate risks and appraisal of integrated adaptation pathways at the city scale, as outlined in Section 5.3. We bring together pathways research for London as this provides the foundation for the development and appraisal of integrated pathways in response to multiple risks. The development and appraisal of pathways for estuarine flood risk (EA, 2012, Reeder and Ranger, 2011), risks to water supply (Kingsborough et al., 2016) and heat risk (Kingsborough et al., 2017) have already been published and are therefore only summarised in Section 5.4. This is, however, the first demonstration of pathways for surface water flooding in London. We also present new pathways for heat risk that incorporates targeted building level adaptation actions. The consolidation of the

evidence base provided by these four pathways and the integrated framework we present has enabled the development and appraisal of an integrated adaptation pathway for London, described in Section 5.5. The results presented are of direct interest to stakeholders in London, whilst the integrated pathways approach and demonstration is informative for actors internationally that are developing long-term city-scale urban adaptation plans, in response to multiple climate risks.

5.3 ADAPTATION APPRAISAL AND DECISION MAKING

The long timeframes inherent to adaptation decision-making require a sequential and iterative process to adequately respond to changes within dynamic urban systems. Flexible decision support tools and methods can provide structure and improve decision-making processes (Jones et al., 2014). An adaptation pathways approach presented for decision-makers as pathways diagrams is an effective decision support methodology as it presents multiples sources of decision relevant information; recognises the influence of uncertainty; and can be used to explore plausible adaptation futures relevant to the development of a long-term adaptation plan (Kingsborough et al., 2016, Haasnoot et al., 2013, Reeder and Ranger, 2011). Pathways diagrams provide a visual representation of the sequencing of decision points and plausible adaptation actions that may be implemented in the future (Kingsborough et al., 2016). This provides decision makers with information that is salient, actionable and based on the best available information.

Adaptation decision support for urban areas is most effective when it adopts a system-wide perspective that dynamically considers the spatial distribution of vulnerability, exposure and climate hazards, as well as the timing, rate and scale of adaptation actions (Vigui and Hallegatte, 2012, Hallegatte et al., 2011, Dawson, 2015, Hall et al., 2009).

We have therefore developed adaptation pathways diagrams that show: (i) indicators of the changing climate hazard; (ii) an exposure indicator; (iii) a dynamic adaptation pathway; and (iv) quantified indicators of climate-risk. These four elements are important for decision-makers to understand the relationship between climate risk and adaptation actions. Options are explored through a range of plausible pathways, and the benefits are quantified through reduced levels of climate risk.

To effectively quantify the costs and benefits of adaptation actions within a complex urban environment, a systems model is needed (Dawson, 2015, Hall et al., 2009). This paper utilises the Urban Integrated Assessment Framework (UIAF) that was developed to facilitate city-scale climate change risk analysis for Greater London (Dawson, 2007, Hall et al., 2010, Walsh et al., 2011). The version of the UIAF used in this study, outlined in Figure 5-1, integrates: an urban spatial Weather Generator (WG); population and demographic projections; impact assessment models for flooding, water supply and overheating; and multiple adaptation levers to represent adaptation actions within the UIAF (further described in Section 5.4).

In most urban adaptation studies there is limited quantification of the extent to which urban adaptation actions are complementary or conflicting (Dawson, 2011, McEvoy et al., 2006, Wilby and Keenan, 2012, Vigui and Hallegatte, 2012, Masson et al., 2014). This framework allows: scenarios of climatic and socio-economic change and adaptation action to be developed; quantification of multiple climate risks and uncertainties; and estimation of the benefits of portfolios of adaptation actions, in an internally consistent manner.

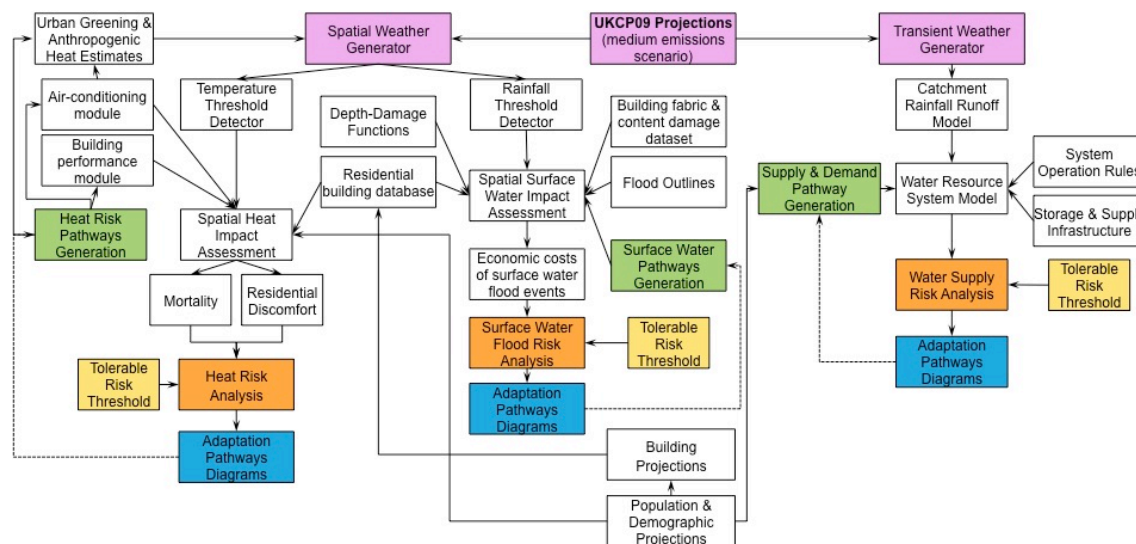


Figure 5-1 Overview of the risk based urban integrated assessment framework that includes: an urban Weather Generator; population and demographic projections; impact assessment models for flooding, water supply and overheating; and multiple adaptation levers

Pathway appraisal was undertaken using the UKCP09 medium emissions scenario, this corresponds to the A1B Special Report on Emissions Scenario (SRES) (Murphy et al., 2009). The SRES A1B is equivalent to a median global mean temperature increase of approximately 2.75°C by the 2080–2100 period (compared with a 1980–1999 baseline); it is positioned between Representative Concentration Pathways 6.0 and 8.5 (IPCC, 2013). The use of a single emissions scenario allowed for consistent climate information to be used across each of the risks. Appraisal across a long time horizon ensured a wide range of climate conditions were considered, however using additional projections, particularly a very high emissions scenario, would allow for further robustness testing of potential pathways.

The appraisal utilised an updated version of the UKCP09 weather generator that produces spatially coherent time series of heat risk and surface water risk assessment (Kilsby et al., 2011) and a transient version for appraisal of water supply risk (Glenis et al., 2015). The use of the UKCP09 projections enabled probabilistic analysis of multiple climate risks as well as providing an assessment of underlying climate model

uncertainties (Jenkins et al., 2014b, Borgomeo et al., 2014). Geospatial asset, hazard and socio-economic data has been utilised to identify high-risk locations and explore the spatial implications of adaptation decisions.

To date the UIAF has not been used to appraise an integrated adaptation pathway. The next section describes adaptation pathways that have been developed for estuarine and surface water flooding, water supply and heat risk, and appraised using components of the UIAF. Section 5.5 demonstrates the full potential of the UAIF to appraise an integrated pathway.

5.4 DEMONSTRATION ADAPTATION PATHWAYS IN LONDON

Warmer, wetter winters and hotter, drier summers are projected for London (LCCP, 2012b). Extreme rainfall events and heatwaves are projected to become more intense (Murphy et al., 2009), and tidal, fluvial and surface water flood risk are projected to increase (EA, 2012, GLA, 2009, Wilby and Keenan, 2012). The Greater London Authority (GLA) is responsible for London-wide strategic planning related to economic and social development and environmental improvement – including climate change adaptation (HM Government, 2007). Adaptation in London is addressed by the London Climate Change Adaptation Strategy (LCCAS) (Nickson et al., 2011) – which identifies estuarine and surface water flooding, heat and water supply as London’s priority climate risks – and through integration of adaptation actions into the London Plan: the city’s framework for spatial planning and urban development (GLA, 2015b). The London Climate Change Partnership brings together public, private and community sector organisations to improve understanding of London’s existing and future climate risks, and to share knowledge as to how organisations are overcoming adaptation challenges (LCCP, 2015).

Key initiatives that contribute to London's climate resilience include: periodic water resources management planning undertaken by London's water companies (EA et al., 2012); the Drain London partnership, addressing city-scale surface water flood risk (GLA, 2012a); implementation of the TE2100 plan for adapting to sea level rise by the Environment Agency (EA) (EA, 2012); development and implementation of the Heatwave Plan led by Public Health England (PHE) (PHE, 2015); and emergency management coordinated through London Resilience (LRP, 2014). Common to all of these initiatives is multi-stakeholder collaboration and recognition of the value of addressing climate at the city-scale.

5.4.1 Estuarine flood risk

An estimated 1.25 million Londoners, 500,000 residential properties, critical government buildings, cultural assets and a wide range of critical infrastructure are located in the Thames tidal floodplain, and therefore vulnerable to flooding if the current flood defences were to fail (EA, 2012). The existing Thames Estuary flood defence system was designed to provide protection from a flood event with a 1 in 1000-year average recurrence interval (estimated for the year 2030). In addition to the Thames Barrier, the flood protection system includes around 400 small barriers and floodgates, and over 300km of river walls and embankments.

Climate change is the largest source of uncertainty affecting the long-term management of the flood defence system, which is projected to be impacted by changes in mean sea level, peak surge tide level, and wave heights. Projections for sea level rise in the estuary by the end of the 21st century extend up to 2.7m with an estimate of 0.96m adopted for informing the identification of a preferred plan, as per Figure 5-2, which

shows a high-level adaptation pathway diagram developed as part of TE2100 (EA, 2012).

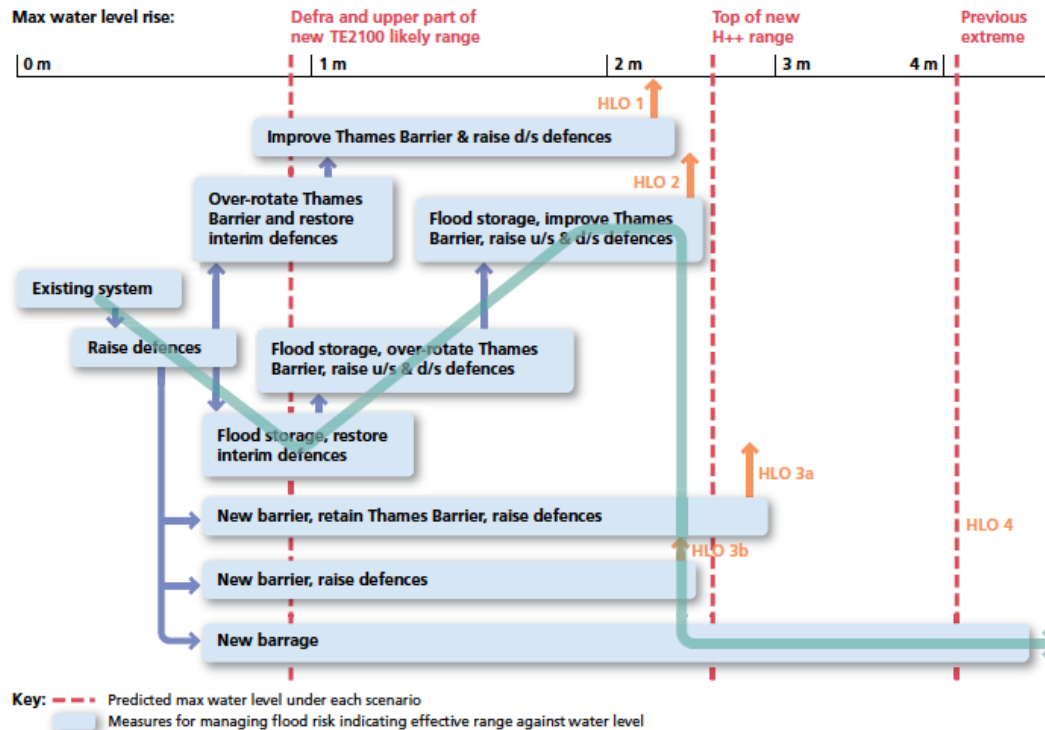


Figure 5-2 TE2100 adaptation pathways diagram – adaptation actions may be implemented when sea level decision thresholds are reached (EA, 2012)

The TE2100 project adopted a policy-first approach: developing the tools, models and methods necessary to identify portfolios of flood management options (Reeder and Ranger, 2011). The development of the TE2100 Plan appraised adaptation portfolios using multi-criteria assessment and the subsequent prioritisation of a preferred pathway (Ranger et al., 2013). The TE2100 preferred pathway includes staged long-term modification of the Thames Barrier with a decision on significant additional measures anticipated by 2050; and the management of fluvial and pluvial flooding through local measures including making space for water, local flood defences, building resilience measures, flood forecasting and emergency planning (EA, 2012).

The TE2100 project monitors 10 adaptation indicators; the outputs from the monitoring programme will inform the scheduled review and re-appraisal of the TE2100 every 10 years. They will also inform the timing of future adaptation actions and trigger decision-making if rapid change occurs in one or more of the indicators (EA, 2012), such as sea level rise thresholds (Reeder and Ranger, 2011).

TE2100 has moved from a planning to implementation phase, which most recently has contributed to better understanding the practical challenges of monitoring and evaluation for adaptation. These lessons have informed the development of pathways for surface water flooding, heat risk and water supply risk discussed in this paper, in addition to a growing number of projects internationally.

5.4.2 Heat-risk

Heat-risk is the least understood of London's priority climate risks and practices for managing long-term heat-risk are the least well established (Zaidi and Pelling, 2015, GLA, 2011b). The combined effects of the urban heat island and climate change are projected to increase summer temperatures and the number of heatwaves in London (McCarthy et al., 2010, Mavrogianni et al., 2011, Murphy et al., 2009). Without proportionate adaptation, increasing heat-risk is likely to result in increasing heat-related mortality (Gasparrini et al., 2015, Hajat et al., 2014, Stone et al., 2014, Taylor et al., 2015b); additional residential overheating (Taylor et al., 2015b, ZCH, 2015, Porritt et al., 2012); and reduced infrastructure performance (Jenkins et al., 2014a).

Heatwave-risk management in London is largely reactive and focussed on a public health response that is operationalised during heatwave events when temperature thresholds are exceeded (Zaidi and Pelling, 2015, PHE, 2015). However, a significant proportion of the heat-related impacts on vulnerable people occur during periods of

moderate heat, outside the actual heatwave events. There is limited consideration of preparedness, long-term risk management or adaptation. There are further challenges due to London's ageing building stock that was designed for a very different, heating-dominated climate, in which building fabrics were designed to capture heat gains during winter rather than enable losses during summer.

Understanding of the effectiveness of localised adaptation actions in London is growing however, including solar shading; building insulation and ventilation (Porritt et al., 2012); roof insulation and window upgrades (Mavrogianni et al., 2012); green roofs (Virk et al., 2015, Virk et al., 2014); and occupant behaviour (Mavrogianni et al., 2014). Reducing indoor temperatures by 1–2°C, to simulate adaptation and acclimatisation, was projected to reduce annual heat-related mortality in London by 32–69% across a range of climate scenarios, relative to a no adaptation scenario, with similar benefits seen for residential overheating (Jenkins et al., 2014b). City-scale adaptation pathways diagrams provide a strategic overview of climate risk and adaptation action. Considering heat-risk at the city-scale requires some simplifying assumptions compared with building or neighbourhood-scale analysis, however it is at the city-scale that many critical decisions are made which affect future heat-risk, including land-use planning and building regulations (Kingsborough et al., 2017). Strategic approaches can be complemented by localised approaches that focus on enhancing institutional capacity and social networks that support resilience to heat-risk (Zaidi and Pelling, 2015).

The application of an adaptation pathways approach to long-term planning for urban heat-risk at the city-scale has been demonstrated for London, with adaptation portfolios comprised of green infrastructure (GI), air-conditioning and building level adaptations

(Kingsborough et al., 2017). This paper incorporates two additional adaptation pathways, referred to as Adaptation+ and Adaptation++. These pathways present the results of the first appraisal of targeted building level adaptation actions across London's building stock in combination with extensive green roofs and urban greening. The building level actions are modelled using the EnergyPlus tool described in Taylor et al. (2015b), adapted to include external window shutters, variations in window-opening behaviour, and future climate scenarios. The buildings themselves have been modelled as being retrofit to their maximum possible levels, as per Taylor et al. (2015a). Portfolios of building level actions to reduce overheating include external shutters, an adaptive approach to window operation, improved building fabric performance (from an overheating perspective), reduced building permeability and ceiling and external cavity wall insulation. The benefits of green roofs and urban greening are modelled as a reduction in the urban heat island, as per Kingsborough et al. (2017). Further benefits of green roofs not quantified as part of this assessment are likely due to their insulating properties (Virk et al., 2014).

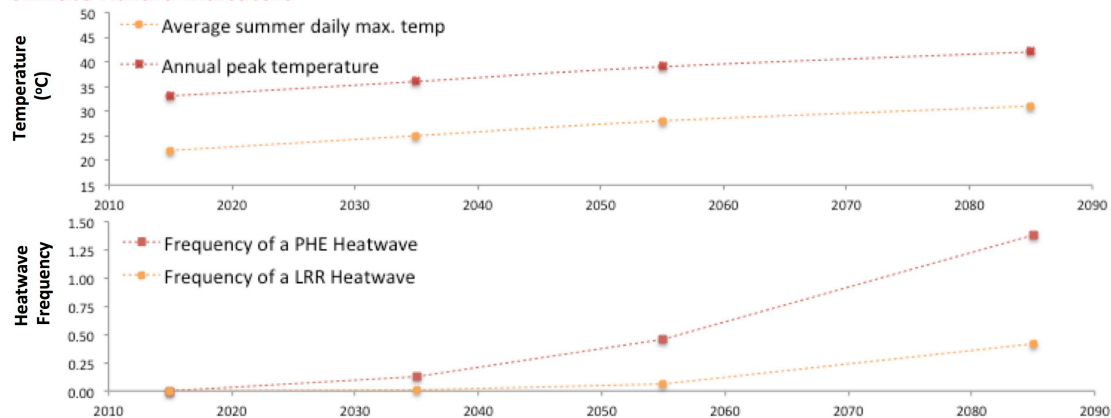
The presentation of a plausible yet ambitious portfolio of heat risk reduction actions is an original contribution that has allowed us to develop an estimate of the potential for building level actions to reduce residential heat risk at the city scale.

Adaptation+ and Adaptation++ are optimistic scenarios from an adaptation and greenhouse gas mitigation perspective. The integrated risk assessment model outlined in Figure 5-1 was used to quantify the impacts of these pathways on reducing residential overheating risk. The results are presented as a component of an adaptation pathways diagram. Figure 5-3 shows a pathway diagram for the Adaptation++ Pathway for heat risk, comprising four panels. The top panel includes two indicators of the

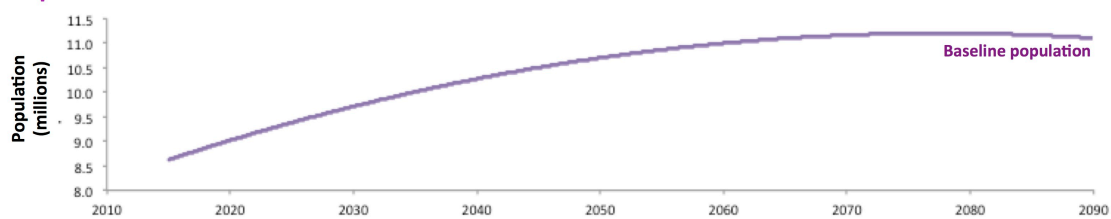
changing climate hazard: changing mean and maximum summer temperatures, and heatwaves as defined by PHE and as part of the London Risk Register (LRR). The second panel is an exposure indicator, represented by London's population. The third panel shows a dynamic adaptation pathway that includes urban greening, green roofs and building level adaptation actions as described above. The bottom panel is a quantified indicator of climate-risk; it compares the results with and without adaptation over time. The risk indicator is the probability that 25% of residents would experience 5 consecutive days of residential overheating. Residents are considered to experience discomfort when internal temperatures exceed 28°C in living spaces, similar to the CIBSE (2006) guidelines, and the results displayed are for the 50th percentile.

Adaptation+ would reduce the median annual probability by 1.81 that 25% of residents in London will experience 5 consecutive days of residential overheating in the 2080s, compared to the no-adaptation scenario, while Adaptation++ would reduce risk by 2.1 in the 2050s and 1.89 in the 2080s (50th percentile, UKCP09 medium emissions scenario). However, even following the Adaptation++ pathway, heat-risk will continue to rise in each future time period compared to the baseline. This reinforces the importance of early warning, emergency response, communication, stakeholder engagement actions, adaptive capacity, and acclimatisation (PHE, 2015, Matthies and Menne, 2009, Hajat et al., 2010, Wolf and McGregor, 2013, Zaidi and Pelling, 2015). Air-conditioning may play a growing role in managing heat-risk; however, increasing air-conditioning will increase the urban heat island causing a negative feedback effect, and may increase greenhouse gas emissions (Kingsborough et al., 2017).

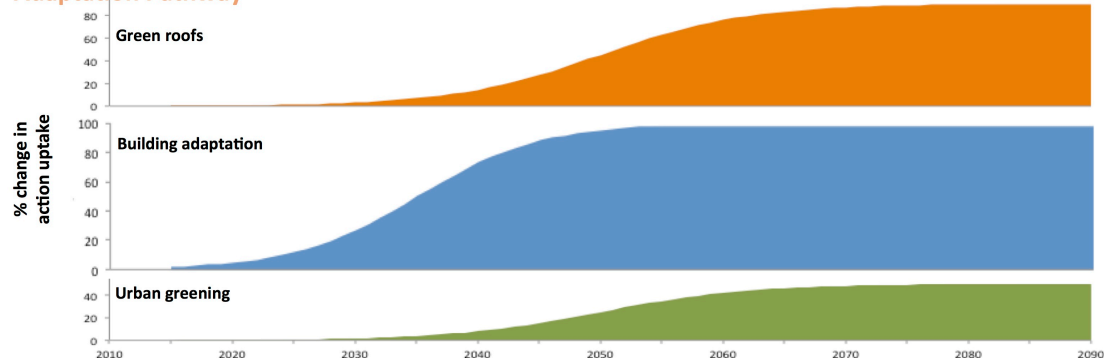
Climate Hazard Indicators



Exposure Indicator



Adaptation Pathway



Risk Projection

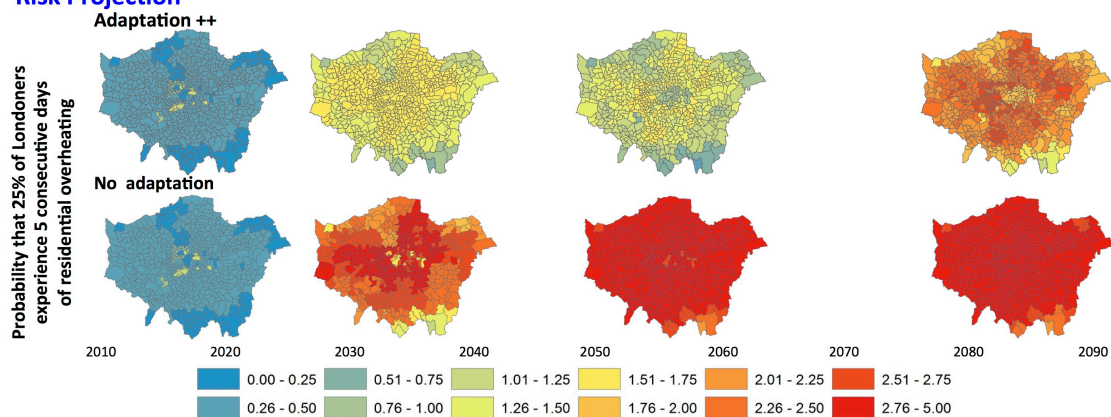


Figure 5-3: Adaptation++ Pathway diagram for heat risk management in London. Actions include increasing the percentage of dwellings with green roofs, upgrading the building stock so it is better adapted to hotter summer temperatures and increasing the area of green space. All actions are implemented following logistic uptake curves with all actions implemented by the 2080s. Risk is reduced in the 2030s, 2050s and 2080s compared to the no adaptation scenario.

5.4.3 *Water supply risk*

London's water supplies are being stretched by increasing population and reducing water availability (EA, 2013). London is classified as a water-stressed city and already faces water scarcity challenges (EA, 2013). Climate change projections for the Thames catchment suggest that by 2040 summer flows and annual rainfall may decrease whilst temperature may increase (Murphy et al., 2009, Diaz-Nieto and Wilby, 2005). Overall water demand is expected to rise due to population growth and increasing single household occupancy (HM Government, 2012). Current water management practices are not well suited for adaptation planning because of the short time horizon considered (25 years), the deterministic approach used to account for climate uncertainty, and the inability to consider transient climate conditions (Hall et al., 2012d).

London's drinking water demands are primarily supplied by surface water abstraction from the Rivers Thames and Lee, and groundwater sources. A desalination plant and reserve aquifers can be activated to supply water to London during times of drought. Significant investment in water resource management is anticipated this century to maintain the existing levels of supply reliability and to account for population growth and climate change (LCCP, 2012b, Kingsborough et al., 2016). Potential water supply actions include new reservoirs, water transfers, artificial recharge, wastewater reuse and desalination; whilst demand management options include leakage reduction, compulsory metering and variable tariffs (GLA, 2012b, GLA, 2011c, Thames Water, 2014). Water resource planning must ensure that a portfolio of actions can be deployed that is proportionate to changing water supply risk, as well as meeting economic, social, technical and environmental objectives (Kingsborough et al., 2016, Borgomeo et al., 2014, Matrosov et al., 2015).

Risk management practices for water supply risk in the UK are well established, and existing levels of water supply risk for London are well managed (Hall et al., 2012d, EA et al., 2012). However, regulatory and methodological barriers have restricted the extent that climate change adaptation has been considered in water resource planning in to date (Hall et al., 2012d). Stakeholders expressed an interest in understanding the potential for adaptation pathways to be used in adaptation planning for water resources in London, so that a planning horizon beyond the existing 25 year timeframe could also be considered (Kingsborough et al., 2016).

An adaptation pathways approach that complements existing water resource management approaches has been demonstrated in London. Portfolios were co-developed and scheduled with stakeholders to represent a range of informative adaptation scenarios. The pathways diagrams represent quantified transient scenarios outlining the trade-offs between risk and investment to 2100. The adaptation pathway diagram in Figure 5-4 brings together four attributes that change over time. The top panel demonstrates how the climate hazard indicator of summer river flow is projected to trend downwards, but is characterised by high year on year variability. The second panel is an exposure indicator that highlights how London's population is projected to grow before levelling off towards the latter part of the 21st Century, with a wide range of uncertainty however. The third panel shows a dynamic portfolio of adaptation actions; in this case demand management actions have been scheduled alongside a new water re-use plant. The bottom panel presents a quantified indicator of climate risk: the probability of water restrictions exceeding an acceptable threshold.

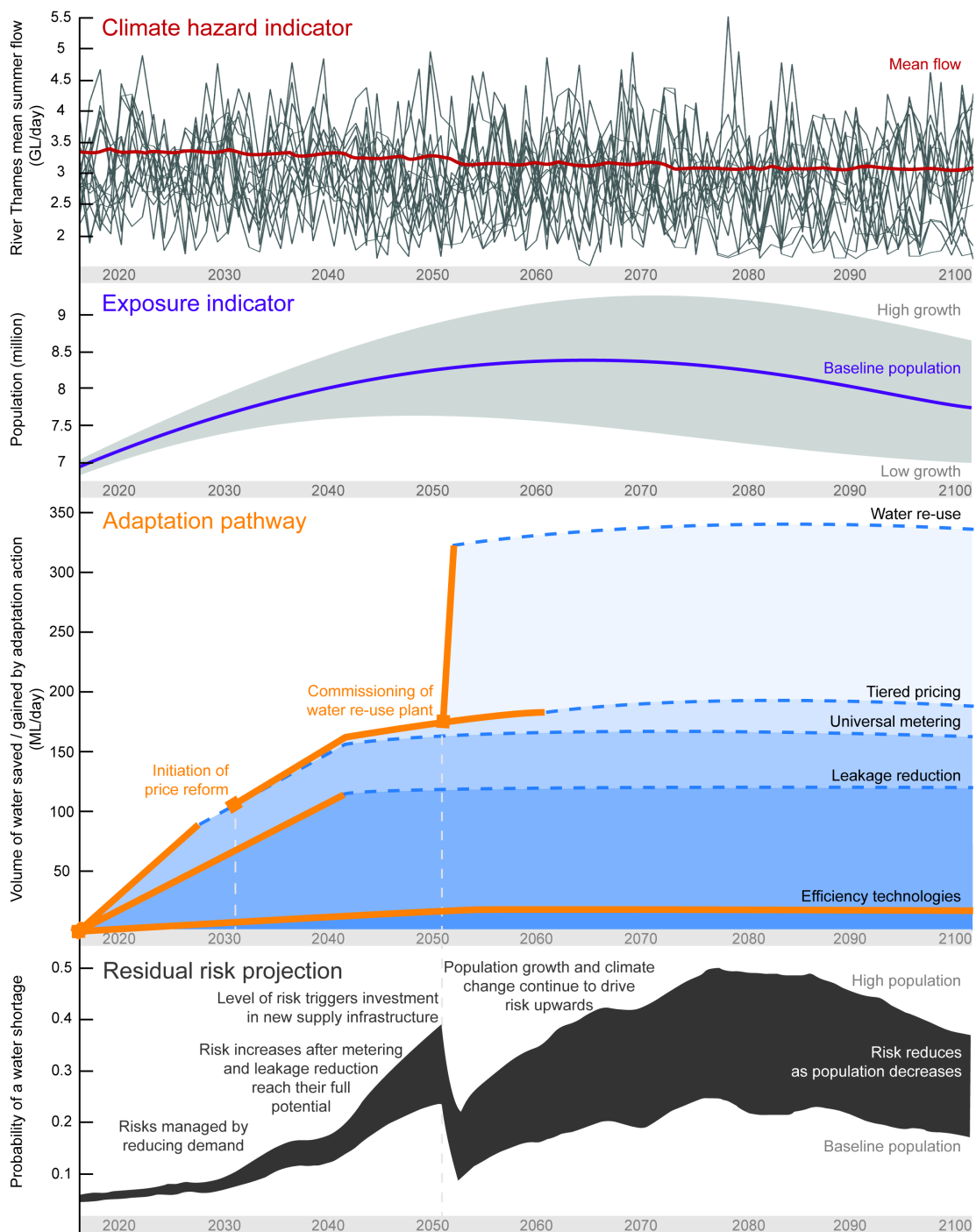


Figure 5-4 Demonstration adaptation pathway diagram for water resource management in London (Kingsborough et al., 2016) This pathway quantifies the effectiveness of a mixed portfolio of supply and demand side actions implemented up to 2100. The range in the risk results reflects the difference between the high and baseline population growth scenarios.

This pathway emphasises the potential for flexible adaptation measures to reduce water demand in the coming decades but anticipates the need for investment in water supply

infrastructure towards the middle of the 21st Century. The effect of this investment on reducing the risk of water shortages is marked; but afterwards, population increase and reducing river flow continue push the risk upwards, with less scope for adaptation through demand reduction. Multiple pathways capable of maintaining the probability of exceeding a target frequency of water use restrictions below a tolerable level through to 2100 have been identified, however, without further adaptation, water shortage risk will increase beyond tolerable levels. Pathways diagrams were successful in allowing further exploration of an extended planning horizon, however further consideration of tolerable levels of risk is required (Kingsborough et al., 2016). Future development of water supply pathways could utilise optimisation approaches to identify pathways that meet multiple objectives for a range of risk thresholds (Mortazavi-Naeini et al., 2014, Beh et al., 2015, Matrosov et al., 2015).

5.4.4 Surface water flood risk

Surface water flooding is London's most likely cause of flooding, and because changing precipitation patterns are projected to increase the number of surface water flood events (Ramsbottom et al., 2012), surface water flooding is a priority climate risk (GLA, 2011b, GLA, 2009). Climate change is projected to increase the intensity and frequency of short duration rainfall events (Westra et al., 2014). Whilst there is a high degree of uncertainty surrounding the scale of change, in the UK the frequency and intensity of extreme rainfall events are projected to increase (IPCC, 2013). Estimates have projected seasonal increases in extreme precipitation of between 5 and 30% by 2070–2100 (Fowler and Ekström, 2009).

In London, city-scale quantified surface water flood (SWF) risk appraisal has been completed, however the effectiveness of city-scale adaptation strategies are yet to be

quantified (GLA, 2012a, GLA, 2015b). This paper presents the first appraisal of city-scale adaptation pathways in response to SWF risk. Appendix A outlines the method developed to quantify the effectiveness of our adaptation pathways. Actions included in two demonstration pathways (Adaptation+ and Adaptation++) include varying amounts of property level protection (PLP) measures and Sustainable Drainage Systems (SUDS) that can reduce surface water flooding by increasing infiltration and delaying runoff (Woods Ballard et al., 2015, Ashley et al., 2015). The results in Appendix A highlight that without adaptation SWF risk is projected to increase but that broad scale adaptation is able to significantly reduce levels of SWF risk.

Figure 5-5 presents a pathway diagram for the Adaptation+ Pathway for surface water flood risk: it includes three panels. The top panel includes the mean return level (across WG grid cells in greater London) for the 1/30, 1/100, and 1/200-year return period events estimated from a generalised extreme value distribution based on hourly rainfall data from the UKCP09 spatial WG for the 2030s, 2050s and 2080s. The 1/100-year return level in the baseline is 20mm/hour and it increases to 24mm/hour in the 2030s but it then plateaus. These relatively small changes are consistent with other studies that have used the UKCP09 data for surface water flood risk appraisal (Jenkins et al., 2016). The central panel of Figure 5-5 highlights a dynamic portfolio of adaptation actions. By the 2050s urban green space increases by 25% and 50% of London's roof area is greened. PLP is installed by 50% of residential dwellings that are within the existing 1/30-year flood zone by the 2080s. In the bottom panel, EAD is used as a risk-based metric that integrates the impact of changing precipitation and adaptation actions. EAD has been calculated at the ward scale and displayed spatially to demonstrate how risk varies across London.

This adaptation pathway is projected to reduce levels of SWF risk relative to the no adaptation scenario in the 2030s, 2050s and 2080s. Because of the slow assumed rate of initial implementation, risk increases into the 2030s but decreases below the baseline level by the 2050s.

The high levels of uncertainty regarding changes to the frequency and intensity of short duration rainfall events (Westra et al., 2014), reinforces the need for flexible approaches. The pathways development for SWF is the least advanced of the four priority risk areas in London and further consultation, consideration of threshold risk levels and decision triggers, and sensitivity testing is required to advance a pathways approach. However a pathways approach in response to SWF risk has demonstrated significant potential, through the development of plausible adaptation scenarios, to contribute to the development of the long-term city scale adaptive approach that is needed in London (GLA, 2011b).

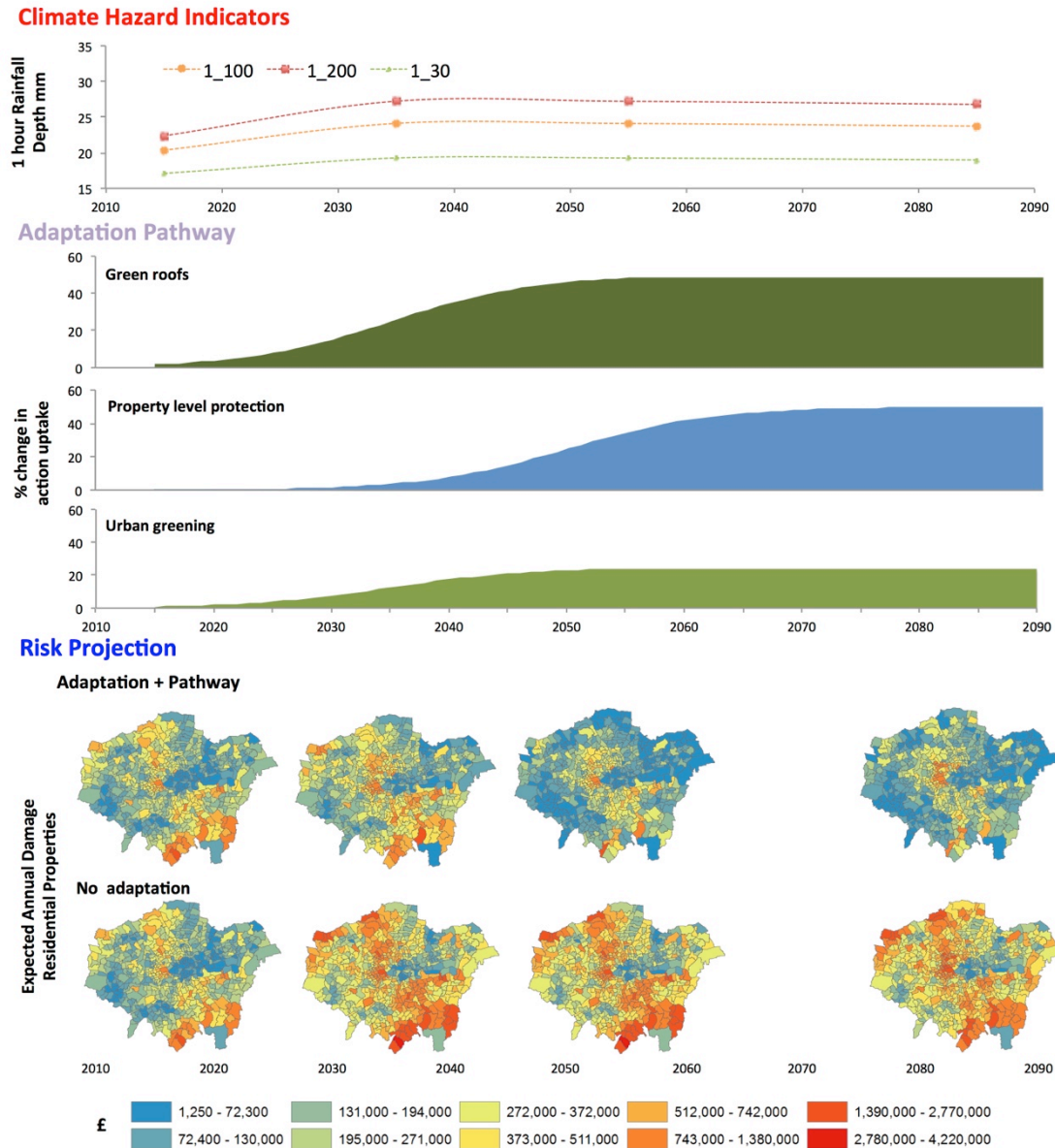


Figure 5-5 Adaptation+ pathway diagram for surface water flooding in London. Actions include increasing the percentage of dwellings with green roofs, installing property level protection so moderate floodwaters cannot enter dwellings and increasing the area of green space to reduce the volume and rate of urban runoff. All actions are implemented following logistic uptake curves with all actions implemented by the 2080s. Risk is reduced in the 2030s, 2050s and 2080s compared to the no adaptation scenario.

5.5 INTEGRATED URBAN ADAPTATION

A number of interactions identified between the climate, climate risks, the urban system, and adaptation actions relevant to London are identified in Figure 5-6. Whilst it is not possible to outline all of the interactions that affect London's climate risk, we have been informed by discussion with stakeholders in London to highlight the material

interactions relevant to the climate risks and adaptation pathways discussed in the previous section.

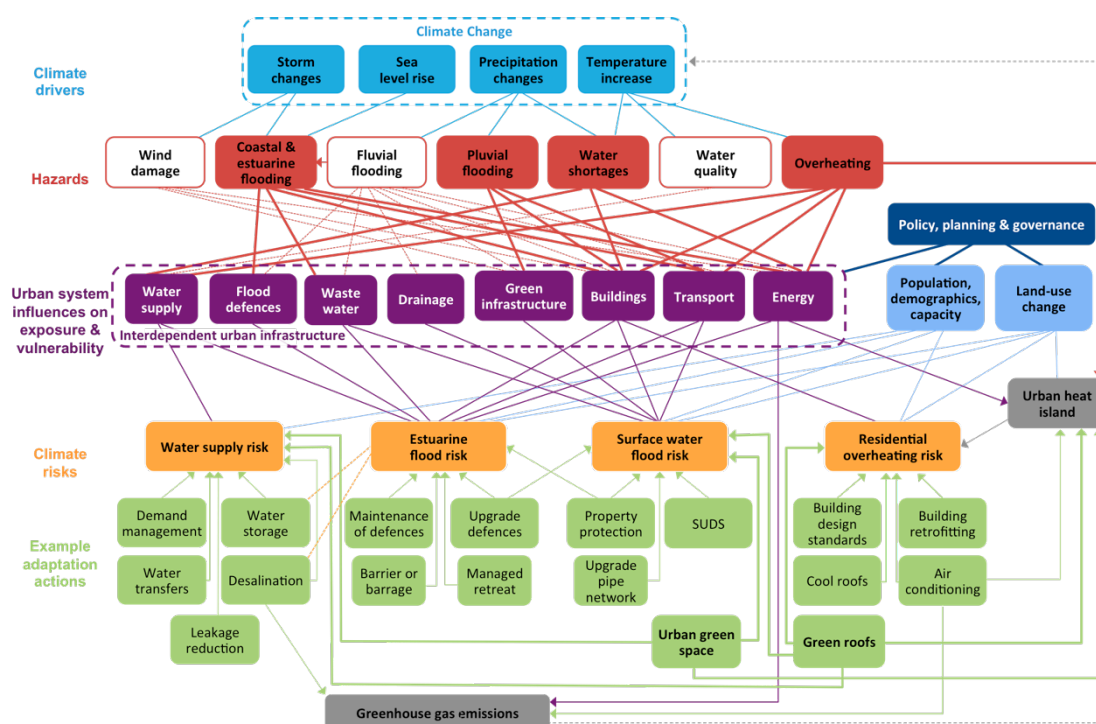


Figure 5-6 Urban adaptation influence diagram identifies interactions between the climate, climate risks, the urban system, and adaptation actions relevant to London highlighting the interdependent nature of urban systems

We adopted two approaches to analyse the extent to which adaptation strategies may affect multiple urban climate risks in London: a qualitative multi-criteria assessment and quantified integrated adaptation pathways appraisal.

Initially, a qualitative multi-criteria assessment of the impact of a range of adaptation actions was undertaken. This appraisal was presented to the members of the London Climate Change Partnership, and stakeholder perspectives on the relative merits of different portfolios were incorporated in the appraisal presented in Table 5-1. Feedback from stakeholders indicated that whilst a qualitative multi-criteria assessment highlighted potential benefits that are not currently captured in existing appraisal techniques, more rigorous methods would likely be required to have influence on future adaptation decisions.

Table 5-1 Qualitative multi-criteria appraisal of adaptation portfolios to explore the potential for adaptation actions to respond to multiple urban climate risk and decision priorities

Portfolio	Adaptation Action	Appraisal					
		Tidal & Fluvial Flooding	Surface Water Flooding	Water Supply	Heat	GHG Emissions	Urban Biodiversity
Behavioural, financial & domestic technologies	Metering (domestic)	0	0	++	0	+	0
	Water pricing (tiered and social tariffs)	0	0	++	0	+	0
	Water efficient technologies (replace shower head)	0	0	++	0	+	0
	Reduction in domestic water-use (shorter showers)	0	0	++	0	+	0
	Reflect relative flood-risk in insurance market	++	++	0	0	0	0
	Minor building retrofit (windows, blinds)	0	0	0	++	+	0
	Adopt personal cooling techniques	0	0	0	++	+	0
	Improve building operation (opening windows)	0	0	0	++	+	0
Green infrastructure	Increase area of green roofs and/or walls	0	++	-	++	+	++
	Rain gardens, on site water storage	0	++	+	+	+	+
	Urban wetlands - detention/retention ponds	++	++	0	+	0	++
	Increase urban tree canopy	0	++	-	++	++	++
	Urban water re-use	0	0	++	0	0	+
Infrastructure	Increase area of cool roofs (high albedo)	0	0	0	++	++	0
	Building renovation (insulation, windows, permeability)	0	0	0	++	++	0
	Install residential air-conditioning	0	0	0	++	--	0
	Maintain urban drainage network	0	++	0	0	0	0
	Upgrade urban drainage network	0	++	0	0	0	0
	Installation of building level flood defences	++	++	0	0	0	0
	Leakage reduction - mains maintenance & replacement.	0	+	++	0	++	+
	Increasing connectivity between water supply regions	0	0	++	0	-	-
	Desalination - water supply	0	0	++	0	--	-
	Groundwater & aquifer recharge	0	0	++	0	-	0
Land-use and spatial planning	Increase area of green space	+	++	-	++	++	++
	Upstream catchment management	+	0	0	0	+	0
	Maintain/increase urban permeability	+	++	0	+	+	+
	Restore natural waterways	++	+	0	+	0	++
	Restrict development in flood plain	++	++	0	0	0	0

Negative Impact	--
Potential negative impact	-
Minimal impact	0
Potential positive impact	+
Positive Impact	++

From the range of adaptations actions identified for London, urban green space and GI were found to have an influence on the largest number of our appraisal criteria. GI may include green roofs, green walls, rain gardens, wetlands, waterways, parks and trees, and can contribute to achieving SUDS and water sensitive urban design (WSUD) objectives, such as improving water quality and reducing urban flooding and drought through storm water retention, infiltration, harvesting and reuse. Many authors have identified GI as a promising urban adaptation action that also contributes to improved social, biodiversity and amenity outcomes (Demuzere et al., 2014, Hoang and Fenner, 2015, Gill et al., 2007, Sussams et al., 2015, Farrugia et al., 2013). Stakeholder discussions reinforced that limited quantified information exists on the effectiveness of city-scale greening strategies that can be used to influence decision-making. As such this was adopted as the focus of the quantified integrated adaptation pathways.

5.5.1 Integrated urban adaptation pathway

The non-linearity of policy interactions in complex urban systems reinforces why it is useful to analyse multiple urban actions and risks in an internally consistent framework (Vigui and Hallegatte, 2012). The urban integrated assessment framework described in Section 5.3 was used to appraise the effectiveness of an adaptation pathway focussing on GI. Our assessment framework and approach also allows us to consider the effectiveness of portfolios of adaptation action in addressing multiple climate risks.

Figure 5-7 is an *integrated urban adaptation pathway* that explores the effectiveness of GI in responding to both heat and SWF risk. The integrated pathway diagram brings together indicators for four attributes of climate-risk: (i) indicators of the changing climate hazard, in this case annual maximum temperature, average summer daily maximum temperature and the 1 hour rainfall depth for the 1 in 30, 1 in 100 year and 1

in 200 year return period precipitation events; (ii) exposure indicators, in this case population; (iii) a dynamic adaptation pathway, in this case green infrastructure actions that are implemented following a logistic uptake curve; and (iv) quantified indicators of heat and SWF risk, in this case the probability that 25% of Londoners experience 5 days of residential overheating and EAD for surface water flood risk. The risk assessment utilised the methods introduced in Section 5.4 for heat and SWF risk. The time dimension provides a sense of the temporal scale at which a pathway is applicable, which assists in visualising the dynamic relationship between risk and adaptation.

Whilst adaptation in London will never focus solely on GI, this pathway illustrates the potential of GI to contribute to managing long-term climate risk. The pathway presented is considered ambitious yet plausible from a GI perspective. Based on spatial analysis of existing land-use (OS, 2015b) this equates to a 25% increase in existing green space at street level (equivalent to vegetating 50% of roadside areas and increasing vegetation cover in private gardens by 75%), and retrofitting 50% of properties with green roofs by the 2050s. At the city scale this corresponds to increasing London's green space from its approximately 760 km² (47%) to 1060 km² (62%).

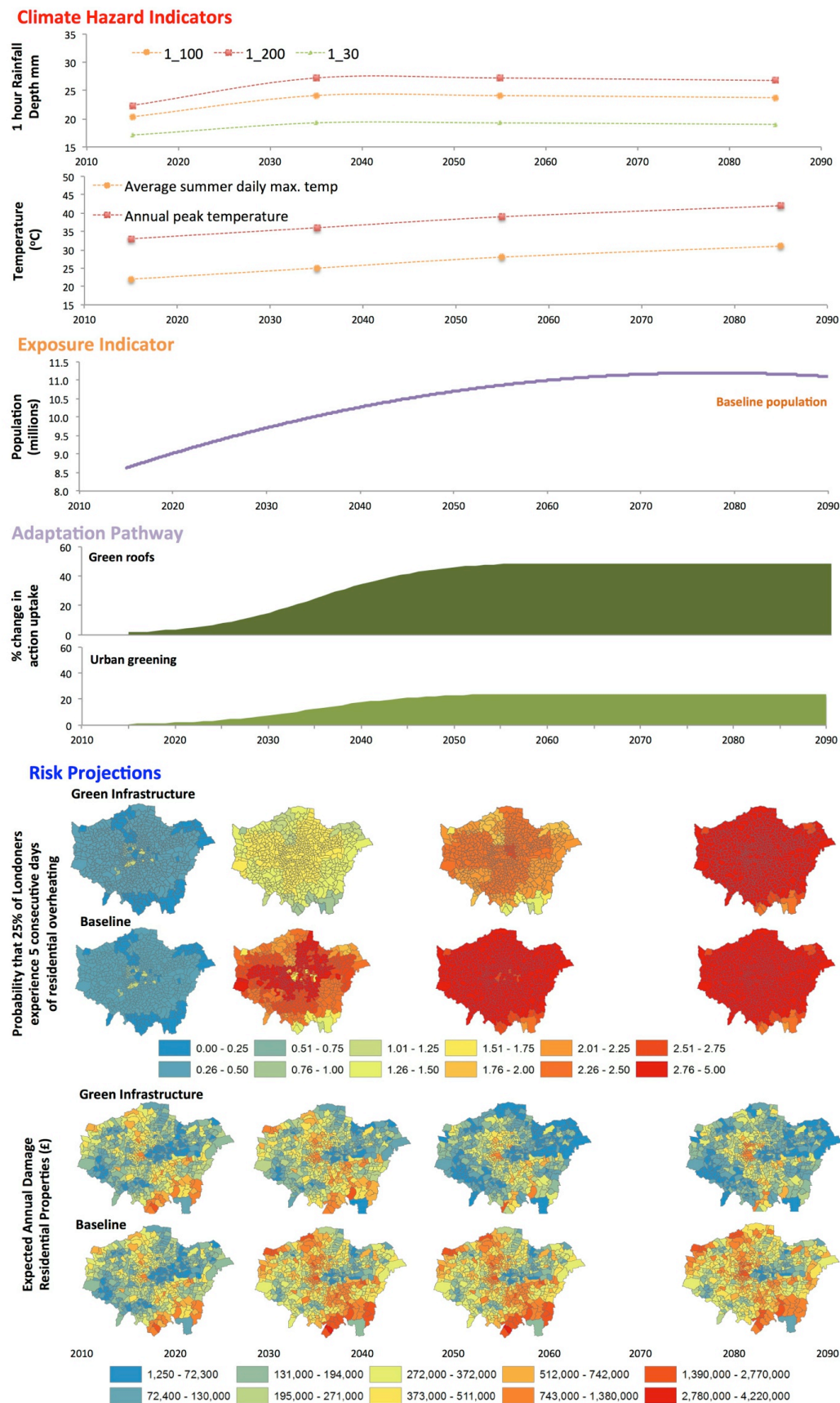


Figure 5-7 Adaptation pathway diagram for green infrastructure in London. Actions include increasing the percentage of dwellings with green roofs and increasing the area of green space both to reduce surface water flood and heat risk. Actions are implemented following logistic uptake curves with all actions implemented by the 2050s.

As per Table 5-2, the results indicate that at the city-scale, increasing GI following our integrated pathway demonstrably reduces heat risk compared to the no adaptation scenario, but it will not reduce the UHI enough to offset the impacts of climate change to maintain existing levels of heat risk. The same portfolio of adaptation actions will reduce SWF risk to below existing levels of risk by the 2050s.

Table 5-2 Actions included in integrated green infrastructure pathway and city scale results for the residential overheating and surface water flood risk

Pathway		Baseline	2030s	2050s	2080s
Baseline	Percentage of Greater London roof area that is green	0	0	0	0
	Percentage increase in green space area	0	0	0	0
	The probability that 25% of Londoners experience 5 consecutive days of residential overheating	0.4	2.66	3.54	4.28
	EAD (£ million)	150.1	302.5	302.5	301.1
Adaptation Green Infrastructure	Percentage of Greater London roof area that is green	0	25	50	50
	Percentage increase in green space area	0	12.50	25	25
	The probability that 25% of Londoners experience 5 consecutive days of residential overheating	0.4	1.47	2.35	3.27
	EAD (£ million)	150.1	195.8	128.0	136.9

Our integrated approach offers the opportunity to consider the benefits of urban greening in terms of reducing heat and SWF risk. Accounting for multiple benefits strengthens the case for urban adaptation based on GI. Increasingly rigorous appraisal at the city scale provides decision makers with the confidence that GI can reduce long-term risks, which strengthens the case for GI solutions compared with alternative heat and SWF risk management actions, such as air-conditioning and piped drainage systems, when developing urban climate policy.

Restricted irrigation and drought can stress GI assets, which reduces their effectiveness in managing heat and surface water flood risk (Coutts et al., 2013). During periods of drought, GI may require irrigation to maximise its effectiveness in moderating the urban climate, which may affect water supply risk, creating trade-off offs between SWF, heat risk and water supply risk (Fam et al., 2008, Li et al., 2014, Coutts et al.,

2013). Evidence from temperate cities in Australia suggests that if sustainable irrigation is adequately considered as part of a GI strategy, trade-offs may be minimised (Coutts et al., 2013). However, further appraisal within our integrated assessment framework would provide the opportunity to consider the impact of GI on water supply risk in London.

As our appraisal was undertaken at the city-scale, we did not quantify specific local benefits such as shading (Rogers et al., 2012, Doick and Hutchings, 2013), the enhanced insulation provided by green roofs (Virk et al., 2014), or specific SUDS actions such as rain gardens. Nor did we quantify the non-climate benefits of GI such as improved local amenity and biodiversity value (Gill et al., 2007, Demuzere et al., 2014). We have however, demonstrated that integrated urban assessment offers the potential to strengthen the case for GI approaches to city-scale urban adaptation. Further consideration of additional criteria, such as cost effectiveness, would strengthen the case for GI as part of any future appraisal.

5.6 DISCUSSION AND CONCLUSIONS

London is a global leader in city-scale adaptation (Rosenzweig et al., 2015, Reckien et al., 2015, Bulla et al., 2014), but it still faces significant challenges in developing and implementing a proportionate, flexible and robust long-term adaptation response to multiple climate risks. Our research found that in London, the institutional structures, created by the long-term commitment of the GLA to climate change adaptation and existence of initiatives like the London Climate Change Partnership, could help to facilitate the implementation of an integrated long-term city scale approach to adaptation. There is a need however, for decision support that builds the evidence base required to prioritise investment of scarce resources towards adaptation. This need is

not unique to London however, as potential investment in long-term adaptation must compete with governments' near-term priorities in many cities (EEA, 2016, Georgeson et al., 2016, Rosenzweig et al., 2015).

A long-term plan reduces the likelihood of mal-adaptation and undesirable lock-in, and builds the political and business cases for integrating flexibility into city planning (Ranger et al., 2013, Payo et al., 2015, Kingsborough et al., 2016). This paper demonstrates how long-term adaptation pathways were developed for London to address its four priority climate risks: estuarine flooding (TE2100), water supply, heat, and surface water flooding. We present a second generation of pathways research to show the potential for adaptation pathways to be used beyond the TE2100 project, and encourage the development and adoption of a flexible, long-term approach to adaptation. Consultation with city level stakeholders from the initial stages of developing adaptation the pathways was critical in reinforcing for decision makers the transient nature of climate change; the uncertainties requiring management; and the ongoing need to identify and monitor climate risk, adaptation and decision relevant metrics. The adaptation pathways diagrams were then an effective tool to assist in communicating the benefits of adaptation action in a salient manner.

To date, most city level adaptation plans still only address individual sectors and/or risks, despite the threat posed by multiple climate risks to cities worldwide being increasingly recognised. There is a need to better account for the complex and interdependent nature of urban systems and demonstrate how integrated adaptation strategies may be appraised. We present an integrated assessment model and demonstrate its use in informing the development and appraisal of an integrated adaptation pathway for London. The model incorporates multiple processes affecting

climate risk, allowing us to capture interdependencies and explore plausible adaptation futures in an internally consistent manner. Our integrated assessment framework: (i) quantifies the effectiveness of adaptation actions in response to multiple risks; (ii) is a decision support tool targeted at city scale appraisal, allowing us to explore the potential for adaptation at a scale relevant to strategic urban decision making; (iii) is risk based, enabling us to incorporate the stochastic processes that affect existing urban risk management and thoroughly consider climate model uncertainty; (iv) uses scenarios to explore futures that cannot readily be assigned probabilities; and (v) considers long-term time scales, particularly relevant to urban adaptation contexts that have a high potential for lock-in or maladaptation.

Our appraisal of London's adaptation pathway in responding to multiple risks is not possible without a spatially explicit, quantified and integrated approach. This approach highlights risk 'hot spots' at the sub-city scale, which may be used to further target adaptation investment in London. With an increased focus on distributed actions (such as domestic water efficiency, property level flood protection, or green roofs) it is likely that households and/or neighbourhoods will follow different adaptive pathways (Câmpeanu and Fazey, 2014), which will impact the pathway realised at the city level. Future research exploring the relationship between nested and/or multi-scale pathways would be informative in this context.

Identifying acceptable and tolerable levels of risk is a key component of a pathways approach because of its direct link to the timing and scale of future investment. Following this demonstration of the potential for risk metrics to be used across each of London's priority climate risks, further research to refine the metrics and to identify decision makers' threshold and decision triggers would be beneficial. A benefit of

combining risk-based and pathways approaches is that residual uncertainty from the risk-based appraisal may be addressed during implementation by adopting a pathways approach. The pathways approach, by reinforcing the role of ongoing monitoring of decision triggers and prioritising flexible actions, puts decision makers in a better position to respond to future conditions beyond those projected than if they had adopted a static plan based on deterministic appraisal.

To avoid risk levels increasing beyond acceptable levels, pathways should be flexible, being updated as new climate and socio-economic information becomes available: if risk increases faster than projected, additional adaptation actions should be brought forward. By considering long-term timeframes, our approach considers a relatively broad range of plausible futures. Future research, however, should further test the robustness of our pathways under even more extreme climate and socio-economic scenarios, as was done through the TE2100 project.

We demonstrate an innovative risk-based approach that utilises an integrated assessment framework to appraise plausible adaptation pathways in response to multiple climate risks. The degree to which city scale governments can apply a pathways approach to adaptation planning and consider urban interdependencies is dependent on local context and capacity. Due to London's longstanding commitment to adaptation and the availability of high-resolution spatial and climatic data, it provides an excellent case study, with the framework able to support the development of integrated risk-based city-scale pathways. More broadly, key elements of an adaptive approach can be adopted for the near term through the prioritisation of short term and flexible adaptation actions; the identification of acceptable risk thresholds and decision triggers; and the implementation of adaptation monitoring and evaluation. Priorities for

developing long-term adaptation plans could include the identification of plausible long-term adaptation pathways and the qualitative appraisal of potential interdependencies. As an initial step we demonstrate that, with stakeholder input, a qualitative multi-criteria appraisal approach can be effective in identifying co-benefits and/or interdependencies that may not be captured in existing appraisal techniques.

London and cities internationally will increasingly need to develop and implement adaptation strategies that consider multiple long-term climate risks. Demonstrating that a system could cope with complex future changes, even if we don't need to act now, provides confidence that a city is able to cope with long-term risk should it adapt in a manner that is proportionate to increasing climate risk.

6 Concluding remarks

6.1 CONCLUSIONS

6.1.1 Delivery against aims and objectives

This thesis set out to develop and demonstrate an improved approach to long-term urban adaptation planning. An adaption planning framework (Figure 3-1) was developed to identify key steps in the development of an adaptation plan and to provide a structure for the specific contributions developed as part of this thesis. The framework is risk-based and iterative, prioritises management of existing risks, and guides the development of long-term adaptation pathways.

Following an initial literature review and the development of the adaptation framework, key research gaps were identified as: (i) adaptation monitoring and evaluation (M&E); (ii) urban adaptation pathways; and (iii) integrated urban adaptation.

The value of risk assessment and M&E in informing adaptation decision-making is increasingly being recognised by both academics and practitioners, however, in practice risk assessment, M&E and adaptation decision-making remain largely disconnected activities. This is in part because the evolution in the practice of adaptation M&E has proceeded largely in isolation from recent developments in risk assessment and decision-making under uncertainty. Chapter 2 grapples with the challenges of how M&E can be effectively incorporated within an iterative risk-based adaptation planning cycle. This thesis' objective in relation to adaptation M&E was to

demonstrate how a framework linking adaptation M&E, risk assessment and decision-making can be used to improve adaptation planning and implementation.

A framework that links adaptation M&E, risk assessment and decision-making, with a focus on the role of adaptation M&E as a means of closing the adaptation policy cycle and embedding learning in future cycles of risk assessment and adaptation action, was developed, as per Figure 2-1. Adaptation in the Thames Estuary was used as a case study as this is a setting where concepts of adaptation planning have been pioneered, but the opportunities of linking to M&E have not hitherto been explored. The framework in Figure 2-2 can contribute to climate change adaptation planning as it provides clarity to stakeholders, and contributes to delivering a compelling adaptation narrative to decision makers.

Practical advantages for city-level decision makers of an adaptation pathways approach include the justification it provides to potentially delay investment until decision thresholds are reached, whilst still providing confidence to stakeholders that a system could cope with future changes, even if we do not act immediately. Since this thesis was commenced in 2012, a pathways approach has increasingly been adopted or promoted in a range of countries and contexts (Barnett et al., 2014, Fazey et al., 2016, Haasnoot et al., 2013, Rosenzweig and Solecki, 2014, Wise et al., 2014, Siebentritt et al., 2014, Lawrence et al., 2013). One example is the London Environment Committee, which has recommended that the Greater London Authority adopt a pathways based approach to adaptation and the management of extreme weather events (LEC, 2015), following a submission informed by research undertaken for this thesis.

The demonstration of how an adaptation pathways approach can contribute to the development of strategic long-term city-scale adaptation planning under conditions of

deep uncertainty was identified as a key objective of this thesis. This thesis has demonstrated how an adaptation pathways approach has helped to reconcile multiple decision timescales. It highlighted the value of strategic long-term adaptation planning to stakeholders by outlining long-term futures that may influence medium-term decision-making. Pathways diagrams have been used to provide a visual representation of the sequencing of decision points and potential adaptive actions that may be implemented in the future.

Demonstrating this approach through its application to a case study allowed for the theoretical and methodological challenges to be better understood, but also a better appreciation of how adaptation pathways principles may be applied in practice. It has also shown that risk-based appraisal can be used to quantify and explore the performance of adaptation pathways in response to multiple climate risks. This work demonstrates how risk-based appraisal may be used effectively in combination with a sequential adaptation pathways approach to decision making under uncertainty.

Chapter 5 explored the potential for integrated adaptation pathways by demonstrating how an integrated assessment framework is used to appraise city-scale adaptation pathways for London that respond to multiple climate risks. The consolidation of the evidence base provided by this research in combination with the new pathways I developed for heat risk and surface water flooding enabled the development and appraisal of an integrated adaptation pathway to capture the co-benefits of adaptation actions.

The adaptation planning framework (Figure 3-1) is flexible and could therefore be adapted for a broad range of adaptation planning contexts. If there is sufficient access to spatial, socio-economic and climate data, and support from the city-level decision

makers, a quantitative risk-based pathways approach could be used to appraise the adaptation pathways in cities internationally.

Adaptation pathways have been used in a range of contexts (Rosenzweig and Solecki, 2014, Haasnoot et al., 2012, Siebentritt et al., 2014, Barnett et al., 2014, Lawrence et al., 2013, Wise et al., 2014, Young and Hall, 2015, Fazey et al., 2016). The most comprehensive urban adaptation assessments have been carried out in cities that are at the forefront of adaptation planning internationally, they include Copenhagen, London, Melbourne, New York, Paris and Rotterdam (Hallegatte and Corfee-Morlot, 2010, Rosenzweig et al., 2015, Georgeson et al., 2016, Hunt and Watkiss, 2010, C40 Cities, 2015). Practitioners and academics in New York, the Netherlands and London continue to exchange and develop ideas related to risk-based approaches to the development and appraisal of urban adaptation pathways.

The number of cities undertaking adaptation planning continues to increase driven by local imperatives and supported by global networks such as 100 Resilient Cities, the C40 Cities Alliance, ICLEI - Local Governments for Sustainability and the Urban Climate Change Research Network (Rosenzweig et al., 2015). There remains, however, significant potential for leading cities to share their experiences and for additional cities to adopt a pathways based approach to adaptation planning that is appropriate to their decision context.

6.1.2 Key elements

The key principles and methods that form the foundations of this approach are described below.

City-scale: Stakeholders from the Greater London Authority identified the need to better understand how climate risk is changing at the city scale and the potential effectiveness of different adaptation responses. It is at the city scale that many critical decisions are made that affect future risk, including land-use planning and strategic infrastructure investment (Hunt and Watkiss, 2010).

Spatial: Climate risks are heterogeneous due to spatial variability of vulnerability, climate hazards and adaptation actions. Appraisal of adaptation pathways has been informed by city scale spatially disaggregated datasets for population, infrastructure, buildings, green space, land-use, flood hazard and the urban heat island in combination with downscaled spatially coherent probabilistic projections of temperature and rainfall.

Long-term: There is significant value in developing a long-term adaptation plan as the consideration of extended time horizons may reduce the likelihood of mal-adaptation and undesirable lock-in, and it builds the political and business cases for integrating flexibility into city level planning. This thesis has provided an approach (shown in Figure 3-1) that considers long-term time horizons and associated deep uncertainties, and has developed tools and methods that have culminated in adaptation pathways diagrams that are able to assist decision makers to create such a plan. The pathways diagrams may be used to explore plausible adaptation pathways from 2015 to the 2080s that are relevant to adaptation planning in London.

Risk-based: A risk-based approach is one that explicitly considers the probability and consequences of harmful events. Risk-based decision making uses evidence of risks to inform individual and societal choices about which courses of action to adopt in the future (Hall and Borgomeo, 2013). A risk-based approach has been adopted in the appraisal of all adaptation pathways, as it is an effective way to account for stochastic

nature of climate hazards. WGs conditioned on the UKCP09 probabilistic climate change projections, that reflect the stochastic nature of weather and climate model uncertainties, have been used in all risk assessment in this thesis. These are the most advanced projections available for London at the time of writing. There are uncertainty factors beyond climate change and a scenario based planning approach has been used to explore future changes in other factors including greenhouse gas emissions, population, land-use and adaptation.

As described in Chapters 3, 4 and 5, in each case I utilised a city-scale risk assessment model to appraise the effectiveness of the adaptation pathways in managing long-term climate risk. Chapter 5 describes how these individual models form a component of a UIAF. There is an increasing emphasis on risk-based approaches in policy making and governance. Demonstrating how risk assessment can be utilised in the appraisal of long-term pathways helps can strengthen the linkages between existing and long-term approaches.

Stakeholder relevant: This research has incorporated stakeholder perspectives to ensure, where possible, that the outputs are credible and decision relevant. Adaptation pathway diagrams, which highlight relationships between climate hazards, socio-economic change, adaptation actions and climate risk in a salient manner, were developed to share results with stakeholders.

Whilst the nature of the interactions with stakeholders was not the focus of the papers presented in this thesis, as part of this this research I interacted with stakeholders from numerous organisations. I maintained an ongoing dialogue with the adaptation team at the Greater London Authority and the Environment Agency's London team. I attended

multiple meetings of the London Climate Change Partnership, where I presented intermediate research findings.

The adaptation pathways in response to water supply risk were co-developed with Thames Water, the Greater London Authority and Environment Agency through multiple meetings to ensure that the pathways appraised were relevant to that decision making context. The development of surface water flood and heat risk pathways was informed by consultations with the London Climate Change Partnership and the Greater London Authority. Because there is no single decision maker with responsibility for managing heat or surface water flood risk in London, I developed a range of pathways representing multiple perspectives that allowed for the exploration of a range of decision relevant and plausible adaptation futures. This research was also the basis of a submission to the Mayor of London's Environment Committee that advocated for adoption of a pathways approach to adaptation planning and improved adaptation M&E (LEC, 2015).

6.1.3 Adaptation Pathways and Robust Decision Making

The integrated framework for adaptation planning (Figure 3-1) outlines how I have conceptualised the relationship between robustness assessment and the development of adaptation pathways. The key element of this framework in this regard is that if long-lived scenario sensitive actions are included in a short to medium term plan, and pathways development and appraisal is not being undertaken, then at a minimum an assessment of robustness should be undertaken. I would however advocate for the development and appraisal of adaptation pathways that effectively explore the broadest possible solution space.

There are significant differences in the way adaptation pathways-based approaches are implemented ranging from the computationally intensive Dynamically Adaptive Policy Pathways based approach utilised by Haasnoot et al. (2013) and Kwakkel et al. (2016) and the more qualitative interpretations of authors including Wise et al. (2014) and Barnett et al. (2014).

Both RDM and Decision Scaling approaches provide insights into conditions under which problems may occur for a decision maker. RDM uses multiple views of the future to identify conditions under which a decision would fail to meet its objectives (Lempert et al., 2006, Lempert et al., 2013, Groves and Lempert, 2007). Decision Scaling focuses on stakeholder-defined thresholds that determine acceptable system performance and the conditions under which these thresholds are exceeded (Brown et al., 2012, Brown et al., 2011b). These structured sensitivity analyses highlight vulnerabilities and assist in making trade-offs transparent (Kwakkel et al., 2016).

Adaptation pathways emphasise the need for dynamic adaptation over time in response to changing levels of risk. They offer the opportunity to demonstrate the portfolio of actions that may be required to manage future vulnerabilities, while emphasising the value of flexibility at the same time. Adaptation pathways approaches also develop a tangible output (pathways diagram) that stakeholders can relate to. This provides community members with confidence that despite increasing levels of risks there is a plausible response that could be implemented if required.

Consistent with the findings of Kwakkel et al. (2016), this thesis has adopted the view that robust decision-making and adaptation pathways are conceptually and practically complementary. The extent, however, to which a robust decision-making or any pathways-based approach may be utilised will in a large part be determined by resource

availability, stakeholders' risk tolerance, and their relative preference for efficiency, flexibility and/or robustness.

From a methodological perspective additional comparisons between RDM and adaptation pathways of the kind completed by Kwakkel et al. (2016) would be beneficial to further explore the complementarities. There is not, however, a need to develop one unifying method for decision-making under deep uncertainty. We should be reminded that all adaptation is local and there is a need to apply methods based on their relative merits and the specific decision context. A greater priority is the need for academics and practitioners to develop their capacity to utilise (and/or appreciate the relative merits of) this portfolio of methods and apply one or more one where most appropriate.

6.2 RESEARCH INTO PRACTICE: BARRIERS AND CHALLENGES

Building consensus on the need for adaptive action and how to best implement it is difficult and requires commitment to a long-term strategic approach (Barnett et al., 2014). Increasing recognition of the need to develop strategic adaptation plans that consider the transient nature of the climate and the uncertainty faced by adaptation decision makers, supports the call for the development and implementation of flexible pathways based approaches to adaptation planning. In London, stakeholders from the Greater London Authority, Environment Agency, London Climate Change Partnership and the London Assembly have expressed significant interest in the potential of a pathways approach (LEC, 2015). There remain, however, barriers and limitations to the implementation of some of the methods presented in this thesis that would need to be addressed.

Governance: A growing literature exists identifying the governance challenges faced in addressing climate change adaptation in London (Porter et al., 2015, Pelling, 2011, Zaidi and Pelling, 2015). This thesis has not sought to specifically identify or address these challenges – such as coordination between the city and borough level stakeholders, and prioritisation of funding – however, they remain a critical barrier to adaptation planning. Furthermore, a lack of political will in the last five years has slowed the progression of London’s adaptation agenda. Despite these challenges, London is recognised internationally as a leading adaptation city (Georgeson et al., 2016, CDP, 2013, Rosenzweig et al., 2015) and has a long-standing history in adaptation and coordinating bodies are in place that facilitate collaboration and information sharing. When the political will and leadership exists, having the adaptation research and stakeholder relationships in place will enable the opportunity to be quickly capitalised upon, as seen in New York City (Rosenzweig and Solecki, 2014).

City-scale: There are limitations to adopting a city-scale approach, including: (i) city-scale adaptation appraisal requires simplifying assumptions compared with building or neighbourhood-scale analysis; (ii) a disconnect between decision-making processes and city-level adaptation can occur as some climate risk and adaptation decisions are made at the national level (i.e. setting water resource planning guidelines and building standards in the UK) and others at the sub-city level (i.e. local development approvals that affect surface water flood risk); and (iii) natural physical boundaries, such as catchments that affect flood risk and water supply, rarely align with city boundaries. Such challenges need to be addressed on a case-by-case basis.

Risk assessment: A risk-based appraisal method can: (i) provide a clear link between near-term risk management practices and long-term pathways appraisal; (ii)

transparently structure a decision problem highlighting the implications of uncertainties on outcomes that society values; (iii) account for the stochastic nature of weather related hazards and climate model uncertainty; and (iv) quantify the benefits of adaptation actions in terms of risks reduced. The risk assessment framework provides a platform around which ideas of tolerable and acceptable levels of risk may be explored for multiple urban climate hazards and use of the UKCP09 projections has provided a tangible description of a future climate that stakeholders considered credible and appropriate for long-term planning.

A risk-based appraisal requires new models, access to high-resolution spatial data sets and a large number of simulations, which may prove difficult in certain contexts. The uptake of a risk-based pathways approach may be problematic as it requires the development and consideration of risk-based metrics that may be unfamiliar to decision makers. Furthermore, where additional financial and technical resources are required, and/or existing levels of risk are perceived to be low, uptake could be challenging. For example, adopting a risk-based approach to heat risk management in London would be a significant practical challenge due to the low perceived existing levels of risk, focus on response as opposed to preparedness, and the limited institutional ownership of heat risk.

Uncertainty: A risk-based approach is most effective when uncertainty can be quantified in probabilistic terms. In conflict with this, long-term climate change adaptation planning may be characterised as an example of decision-making under deep uncertainty. I have found, however, that adaptation pathways and risk-based approaches are complementary because the residual uncertainty from the risk-based appraisal may be addressed by adopting an adaptive approach to decision-making and

implementation. The pathways approach, by reinforcing the role of ongoing monitoring of decision triggers and prioritising flexible actions, puts decision makers in a better position to respond to future conditions beyond those projected. If the frequency of undesirable outcomes increases beyond acceptable levels, additional adaptation actions should be brought forward. In addition, the probabilistic analysis presented in this thesis may be complemented by robustness testing of assumptions (Moody and Brown, 2013, Nazemi and Wheeler, 2014, Herman et al., 2015).

6.3 FUTURE WORK

There is future work that could be undertaken to build on multiple components of the research presented to continue to advance adaptation appraisal and the development of urban adaptation pathways.

Climate scenarios: This thesis has considered a single emissions projection, which would be enhanced by considering a broader range of emissions projections, particularly a very high-end scenario that would allow for further robustness testing of potential pathways.

Model development: This thesis has described individual risk assessment models that have been used to appraise future levels of risk with and without adaptation. Chapter 5 describes how these models may be utilised as part of an integrated assessment framework. There are many ways in which the individual models may be refined and tweaked, but there are two major pieces of model development that would be a significant contribution. First would be to develop the code necessary to allow for portfolios and pathways to be endogenously generated in response to a set of decision rules and future climatic and socio-economic futures. This would allow for a broader

range of pathways to be evaluated. Second would be to rebuild the component models from the ground-up to more seamlessly allow for exploration of integrated adaptation pathways and the potential generation of pathways diagrams as direct model outputs.

More adaptation actions: Aligned with the model development, but a significant piece of research in its own right, would be the quantification of a broader range of adaptation actions. This could include actions in response to heat, such as modifying albedo, consideration of aquifer storage and recovery to reduce water supply risk, or retention and detention structures to reduce surface water flooding. Increasing and diversifying actions would allow for enhanced representation of the plausible range of adaptation benefits.

Thresholds and triggers: Adaptation requires a balance to be struck between decision framing, appraisal, planning and implementation. Arguably a pathways approach can be developed with limited appraisal of existing and future risks, as long as commitment to an adaptive pathways approach is established, decision triggers are identified, and monitoring is commenced. However, given the demand from the public and private sectors and regulatory authorities for increasingly rigorous appraisal in London, as in many other cities, I have prioritised the demonstration of appraisal methodologies that are consistent with an adaptation pathways approach. Because of this, less attention has been paid to the identification of the tolerable levels of risk and the decision triggers for the Greater London Authority within this thesis.

The degree to which the risk-based metrics and decision triggers used in Chapters 3, 4 and 5 were co-developed has varied due to the focus of each paper. However, the further co-development and testing of risk-based metrics and decision triggers with

stakeholders are a promising area for future work that could build upon the methods and models developed in this thesis.

This research has focused on climate risks as a decision metrics, with cost effectiveness also considered in relation to water supply risk. Future work could consider a broader range of metrics potentially including metrics for greenhouse gas emissions (as per Dawson (2015) and Masson et al. (2014)), flexibility and robustness (as per Herman et al. (2015), Beh et al. (2015) and Moody and Brown (2013)).

Monitoring and evaluation: Chapter 2 outlines a framework that integrates three processes requiring alignment to create an iterative planning cycle: risk assessment, M&E and adaptation decision-making. The framework was then applied for the Thames Estuary, highlighting aspects of planning that could be improved and demonstrating how indicators can be used to inform trigger-based decision making. Future work to apply the risk assessment, M&E and adaptation decision-making framework at the city-scale, through a London wide case study, would allow for further testing of the framework. This could include working with the Greater London Authority, who are grappling with the challenges of city-scale adaptation M&E, and should include the identification of specific methods, metrics and processes required to develop and implement an iterative city scale adaptation planning approach.

Expanded utilisation of risk-based appraisal: Climate risk assessment is increasingly used in adaptation policy development, such as the UK Climate Change Risk Assessment (HM Government, 2012). There remain, however, only limited demonstrations of approaches that appraise the benefits of adaptation actions alongside climate risk. The adaptation pathways presented in this thesis were developed for London, but the methods could be applied to different cities in the UK and

internationally, provided the necessary relationships with decision makers could be developed and sufficient data was available.

An additional area for future work is the exploration of nested adaptation pathways. Research could seek to demonstrate the potential for sub-city scale pathways (such as at the borough, ward, or neighbourhood scale in London) that contribute to city scale objectives but potentially have locally relevant actions, triggers and thresholds.

Co-development: This thesis has not delved into the social science of how methods are used, and whether (and in what circumstances) they actually help decision-making. Such research would require a carefully designed social science methodology. It is observed, however, that for adaptation researchers to see further uptake of this research it is incumbent we continue to co-develop adaptation portfolios and pathways, working in an iterative manner with decision makers sharing ideas and improving outputs. One practical method for advancing the uptake of risk-based, city-scale, long-term pathways in London would be to run extensive simulations that effectively sample the plausible scenario space (including hazard, exposure and adaptation scenarios), and then develop a visual pathways interface to allow stakeholders to dynamically and quickly explore the implications of varying hazard, exposure and adaptation scenarios on climate risk.

Appendix A

CALCULATION OF THE EFFECTIVENESS OF ADAPTATION ACTIONS ON SURFACE WATER FLOOD RISK

The method described in this appendix builds on the method detailed in Jenkins et al. (2016), to link high spatial resolution probabilistic projections of hourly precipitation with detailed surface water flood depth maps to estimate surface water flood risk under a range of adaptation scenarios. Detailed surface water flood depth and extent maps for 1/30, 1/100, and 1/200-year return periods generated by the Drain London project were used as the basis for calculating flood damages in the baseline period. By overlaying these surface water flood maps onto GIS data of the location of residential buildings the potential economic damage to building fabric and contents are calculated using flood depth-damage functions (Jenkins et al., 2016, Penning-Rowsell et al., 2016). We did not consider future changes in the number, spatial pattern or economic value of residential buildings.

The return level (rainfall depth) for extreme precipitation events of 1/30, 1/100, and 1/200-year return periods were estimated for the baseline period (1961–1990) using hourly rainfall data from a spatial version of the UKCP09 WG (Kilsby et al., 2011). These rainfall depths are used as thresholds to investigate the change in frequency of rainfall events of a given magnitude under future climate scenarios. This event set is combined with spatial damage functions to estimate Expected Annual Damages (EAD) as an economic measure of surface water flood risk.

Definitive information on observed and predicted changes in sub-daily rainfall in the UK is not yet available (Jenkins et al., 2016). The UKCP09 projections provide information on future climate change at the daily level and the relationships used for generating hourly values are derived from observed rainfall data. New types of hourly weather behaviour, such as more intense thunderstorms, are not explicitly reproduced by the WG for future periods (Jenkins et al., 2016). Despite this the rainfall information derived from the downscaled spatial weather generator is considered the best available for estimating future surface water flood risk in London.

Adaptation pathways were developed to explore the effectiveness of adaptation actions in response to SWF risk. Actions included in the pathways include property level protection (PLP) measures, that prevent water from entering individual buildings (ASC, 2012), and SUDS that can reduce surface water flooding by increasing infiltration and delaying runoff (Woods Ballard et al., 2015, Ashley et al., 2015). SUDS and PLP actions are included in the pathways as they are spatially distributed actions that can be deployed in a flexible manner and therefore well suited to an adaptive approach (Stovin et al., 2013, Woods Ballard et al., 2015, Lamond et al., 2015), and both measures are recommended and highlighted as important approaches to manage future SWF risk in England (Pitt, 2008).

By excluding water from individual properties, PLP is assumed to reduce damages to 25% of the amount that would have occurred without PLP for flooding up to 0.6m (Thurston et al., 2008, Jenkins et al., 2016, Penning-Rowsell et al., 2016). The effectiveness of SUDS was explored by varying land-use type within our model. Consistent with the approach adopted by Sayers et al. (2016), increasing the area of permeable green space relative to hard impermeable areas is assumed to decrease the

rate of rainfall runoff. As such larger rainfall events are required to generate the same runoff depth. The modified rainfall depths have been used as scenario specific thresholds in the impact analysis. Multiple adaptation pathways comprised of SUDS and PLP were developed.

We calculate that during the baseline period, 299,000 residential properties in London are at risk from a 1/30-year event, increasing to 364,000 in a 1/100-year event and 410,000 in a 1/200-year event, which corresponds to EAD of £150 million.

These results are consistent with the study of Jenkins et al. (2016), which estimated EAD for surface water flooding in Greater London to be £171 million, £343 million and £390 million for the baseline, 2030 high and 2050 high climate scenarios. The differences here reflect slight differences in the geographical coverage of the study area; differences in the climate scenarios used; and reflect the use of the updated 2016 MCM depth-damage data, which suggests lower estimates of household flood damage than the previous version. The results of the study here are also consistent with the recent study by Sayers et al. (2016) that estimated EAD for surface water flooding to be £200 million for the whole of England. Without adaptation EAD is projected to increase to more than £300 million in the 2030s. As per Table A-1, our results indicate that in London increasing urban green space by 25%, increasing the area of London's roofs that are green, and by installing property level protection in 25% of residential dwellings that are within the existing 1/30-year flood zone across Greater London could reduce EAD by £184 million in the 2050s compared to a no adaptation scenario.

These results highlight that without adaptation SWF risk is projected to increase but that broad scale adaptation is able to significantly reduce levels of SWF risk below current levels experienced in London. These results also highlight that without

adaptation EAD is projected to increase significantly from the baseline period to the 2030s, but then is projected to plateau in the 2050s and 2080s.

Table A-1 Uptake of adaptation actions included in demonstration pathways for surface water flood risk and the corresponding expected annual damages

Pathway		Baseline	2030s	2050s	2080s
Baseline No Adaptation	EAD (£ million)	150	303	303	301
	Percentage of Greater London roof area that is green	0	25	50	50
	Percentage of at risk of dwellings with PLP	0	12.50	25	50
	Percentage increase in green space area	0	12.50	25	25
Adaptation + SWF risk	EAD (£ million)	150	188	118	126
	Percentage of Greater London roof area that is green	0	41	82	82
	Percentage of at risk of dwellings with PLP	0	10	50	100
	Percentage increase in green space area	0	4	35	50
Adaptation ++ SWF risk	EAD (£ million)	150	215	77	53
	Percentage of Greater London roof area that is green	0	41	82	82
	Percentage of at risk of dwellings with PLP	0	10	50	100
	Percentage increase in green space area	0	4	35	50

EAD has been calculated at the ward scale and displayed spatially to demonstrate how risk varies across London. The highest levels of EAD are observed in wards in southeast London, which is due to the extent and depth of SWF and the high value of the residential building stock. The adaptation pathways are projected to reduce levels of SWF risk relative to the no adaptation scenario in the 2030s, 2050s and 2080s. Because of the slow assumed rate of initial implementation, risk increases into the 2030s but decreases below the baseline level by the 2050s. Across Greater London the Adaptation+ pathway is projected to reduce EAD by £175 million in the 2080s, compared to the no-adaptation scenario.

Appendix B

Table B-1 Impact of urban greening on overheating risk in London

Emissions scenario	Adaptation scenario	Decade	% of residents at risk from overheating, per daily event			Annual heatwave frequency		
			p10	p50	p90	Level 1 p50	Level 2 p50	Level 3 p50
Medium	Business as usual	Baseline	0.03	0.18	0.96	0.07	0.07	0.06
Medium	25% increase in green space	2030s	0.04	0.49	1.00	1.02	0.73	0.53
Medium	Green roof saturation	2030s	0.04	0.50	1.00	1.07	0.77	0.56
Medium	Business as usual	2030s	0.04	0.45	1.00	1.06	0.74	0.52
Medium	25% decrease in green space	2030s	0.05	0.53	1.00	1.20	0.87	0.65
Medium	50% increase in green space	2050s	0.05	0.73	1.00	1.79	1.40	1.13
Medium	25% increase in green space	2050s	0.05	0.74	1.00	1.88	1.47	1.18
Medium	Green roof saturation	2050s	0.05	0.75	1.00	1.95	1.53	1.23
Medium	Business as usual	2050s	0.05	0.76	1.00	1.99	1.57	1.26
Medium	25% decrease in green space	2050s	0.05	0.77	1.00	2.09	1.66	1.34
Medium	50% decrease in green space	2050s	0.05	0.79	1.00	2.25	1.81	1.47
Medium	50% increase in green space	2080s	0.06	0.92	1.00	2.77	2.45	2.21
Medium	25% increase in green space	2080s	0.06	0.92	1.00	2.84	2.50	2.23
Medium	Green roof saturation	2080s	0.06	0.92	1.00	2.90	2.55	2.28
Medium	Business as usual	2080s	0.06	0.92	1.00	2.94	2.59	2.32
Medium	25% decrease in green space	2080s	0.07	0.93	1.00	3.04	2.67	2.40
Medium	50% decrease in green space	2080s	0.07	0.93	1.00	3.18	2.80	2.51

Table B-2 Projected heat-risk in London, adapting the existing building stock so that every building's overheating performance is upgraded to a level equivalent to the current best performer for a given building type

Emissions Scenario	Adaptation Scenario	Decade	% of London residents at risk from overheating, per daily event			London annual heatwave frequency		
			p10	p50	p90	Level 1 p50	Level 2 p50	Level 3 p50
Medium	100 % buildings upgraded	Baseline	0.03	0.14	0.95	0.07	0.06	0.04
Medium	Business as usual	Baseline	0.03	0.18	0.96	0.07	0.07	0.06
Medium	100 % buildings upgraded	2030s	0.04	0.30	1.00	0.77	0.52	0.36
Medium	Business as usual	2030s	0.04	0.45	1.00	1.06	0.74	0.52
Medium	100 % buildings upgraded	2050s	0.05	0.60	1.00	1.62	1.25	1.00
Medium	Business as usual	2050s	0.05	0.76	1.00	1.99	1.57	1.26
Medium	100 % buildings upgraded	2080s	0.05	0.89	1.00	2.64	2.29	2.03
Medium	Business as usual	2080s	0.06	0.92	1.00	2.94	2.59	2.32

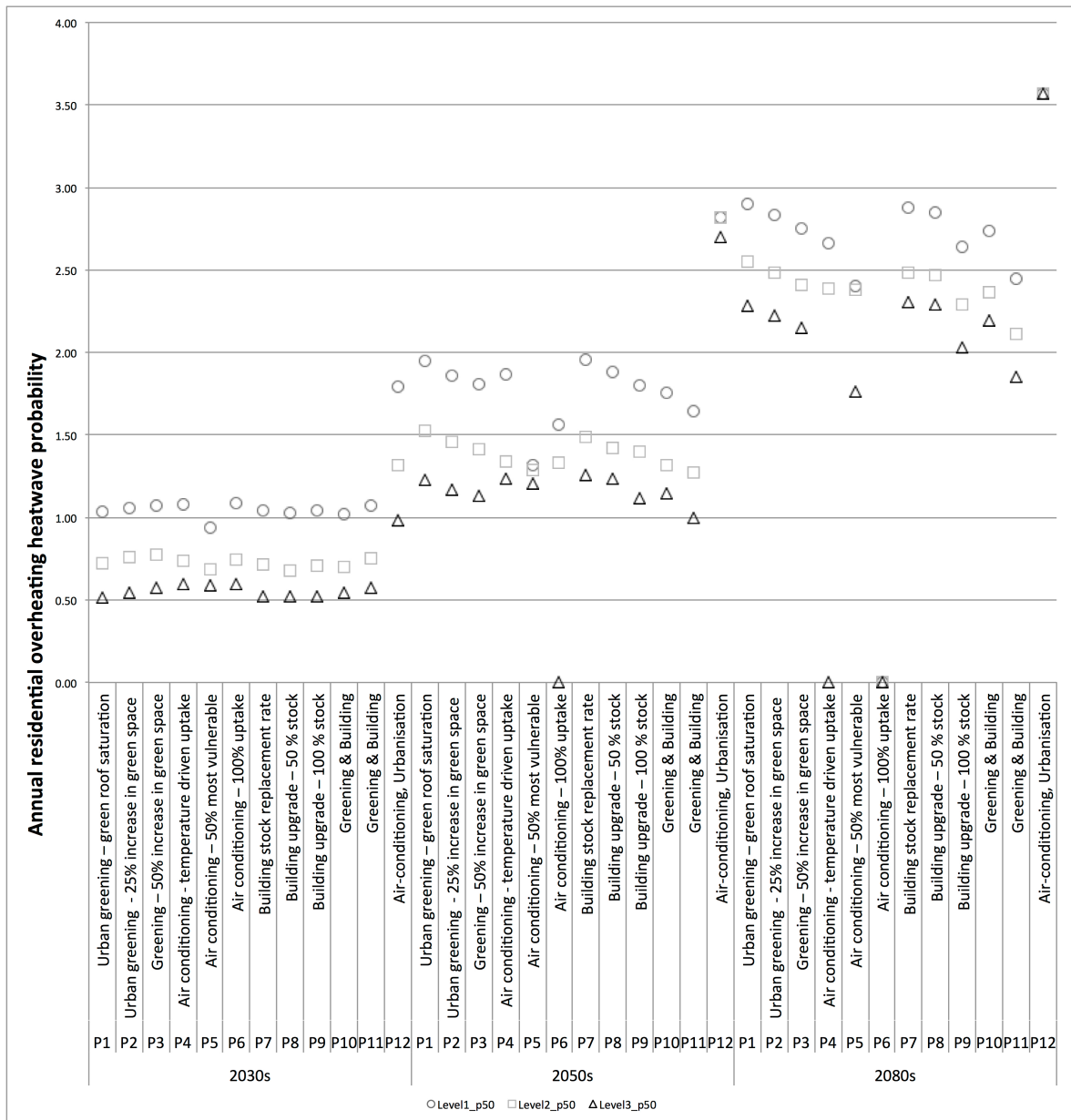


Figure B-1 Median values for London's average annual probability for Level 1–3 heatwaves for each adaptation pathway

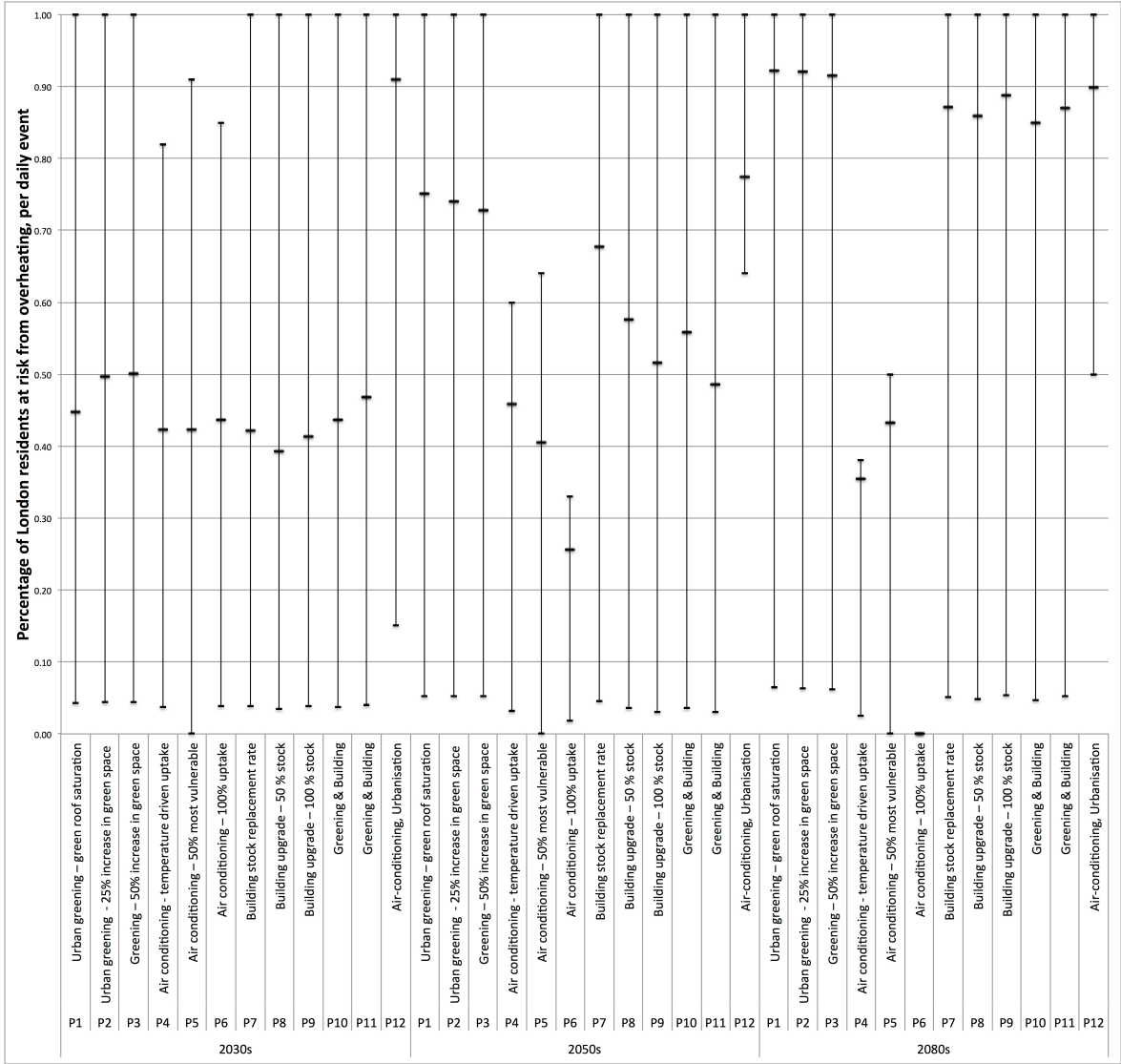


Figure B-2 Median values for percentage of London residents at risk from overheating, per daily event for each adaptation pathway (p10 and p90 are lower and upper bounds)

Appendix C

STAKEHOLDER ENGAGEMENT IN LONDON

Scope of stakeholder engagement

The focus of this thesis was on demonstrating how adaptation pathways could be used to support urban adaptation decision-making, within an overall framework for adaptation planning and demonstrating that quantified risk assessment can be used to appraise the effectiveness of long-term urban adaptation pathways. Prior to the commencement of this thesis it was uncertain if city scale adaptation analysis was possible and what types of actions could effectively be incorporated in urban adaptation pathways.

It was outside of the specific scope of this thesis to specifically co-develop adaptation pathways that would be used in the development of an adaptation plan for London. However, a significant amount of stakeholder interaction was undertaken to, where possible, ensure that the analysis and pathways diagrams that were developed were of relevance to stakeholders in London and ensure that as decision support tools the pathways diagrams were credible and salient.

This appendix provides: (i) additional contextual information on adaptation planning in London; (ii) an overview of the stakeholder engagement undertaken throughout the development of this thesis; (iii) a series of lessons learned regarding working with stakeholders in adaptation planning; and (iv) principles for overcoming adaptation challenges observed during the development of this thesis.

Background on climate change adaptation planning in London

London is the capital of the United Kingdom (UK), located in southeast England on the banks of the River Thames. It is the economic engine of the UK and is an international mega-city that prides itself on leading the world in a broad range of sectors.

The Greater London Authority Act (1999) established the Greater London Authority (GLA) as the entity responsible for London-wide strategic planning related to economic and social development and environmental improvement across Greater London. It shares local government powers with the councils of 32 London boroughs and the City of London Corporation.

The 2007 GLA Act enshrines the Mayor of London with the responsibility to assess and respond to the consequences of climate change adaptation and mitigation for London (HM Government, 2007). The GLA has developed a climate change adaptation vision, this is for a city that:

- is resilient to all but the most extreme floods and has robust emergency plans to respond to, and recover from, flooding;
- has a sustainable balance of supply and demand for water, and is more robust to drought;
- is a comfortable and healthy city to live, work and play in; and
- has a robust emergency plan for heat waves (Nickson et al., 2011).

Taking action to prepare for changes in climate is considered by the GLA to be a cost effective measure to help to protect London from extreme weather and put it on the road to greater resilience against future challenges (GLA, 2011a). Given London's

strategic importance and high levels of international connectivity any negative climate impacts will have repercussions across the UK and internationally (GLA, 2011a).

London is a complex urban environment with a large number of actors who have an important role to play in increasing London's resilience and adapting to climate change. London's adaptation partners are drawn from a range of institutions, communities and individuals across multiple governance levels. Critical institutions that have responsibilities and contribute to managing and responding to existing risks and adapting to climate change include:

- Local Government through the 32 London Boroughs and the City of London;
- National Government bodies including the Environment Agency, the Department for Environment, Food and Rural Affairs (DEFRA) and the Water Services Regulation Authority (Ofwat);
- GLA functional bodies including Transport for London and London Fire and Emergency Authority;
- Private sector utilities including Thames Water, Veolia Water, Essex and Sussex Water and Sutton and East Surrey Water; and
- Partnerships including the Drain London Partnership, London Resilience Partnership and the London Climate Change Partnership.

Nature of stakeholder engagement

Stakeholder interactions undertaken as part of this thesis included, but were not limited to:

- Semi-structured interviews with key informants from the Greater London Authority (GLA), Environment Agency (EA) and Thames Water (TW) to

identify near and long-term priorities for their organisations, ways in which they may or may not be affected by climate change, and perceived barriers and enablers in adapting to climate change.

- Three workshops with the long-term water planning team from Thames Water to: (i) establish the scope and potential for adaptation pathways; (ii) identify actions and pathways (iii) present and discuss the results of the analysis.
- Multiple meetings of the London Climate Change Partnership – a collection of organisations that contribute to increasing London’s climate change preparedness - were attended in 2013 and 2014. Mock-ups of adaptation pathways diagrams were presented and feedback was gathered. A draft of the qualitative multi-criteria assessment for the integrated adaptation pathways was presented. Stakeholder perspectives on the relative merits of different portfolios were incorporated in final appraisal.
- Multiple meetings of the London Working Group on Heat Risk – a collection of organisations that contribute to developing an approach to heat-risk management for London under a changing climate - were attended in 2014 and 2015. Mock-ups of adaptation pathways diagrams were presented to the working group and feedback was gathered.
- Meeting with GLA staff members to discuss the structure of a potential adaptation M&E approach to be adopted in London.
- Presentation of evidence to the London Environment Committee investigations on the impacts of climate change on London’s economy and on adaptation to the risks of severe weather in London.
- Ongoing conversations with practitioners from the GLA and EA to continue to understand the evolving adaptation planning landscape in London.

Lessons learned for working with stakeholders in adaptation planning

The focus of this thesis was not the nature of the stakeholder interactions in co-developing adaptation pathways or an adaptation plan for London - these have nevertheless been identified as key areas for additional research. However, a number of observations from working with stakeholders to refine concepts and outputs were generated as part of this research. These include:

- Establishing reasonable expectations and identifying mutually beneficial objectives is a critical component of any initial interactions with stakeholders.
- Discussions with members of the Environment Agency team who contributed to the development of the TE2100 Plan reflected that it would have been very useful to have access to a mock-up of a pathways diagram early in the development of the project as a tool to communicate key concepts with stakeholders. This ‘lesson-learned’ was adopted through the research undertaken for this thesis. Figures C-1 to C-2 are examples of the pathways diagram ‘mock-ups’ that were shared with stakeholders prior to the development and refinement of quantified pathways diagrams.
- Providing intermediate outputs to stakeholders and allowing outputs to evolve as part of an iterative process was time consuming, however this allowed for stakeholders to develop an enhanced understanding of the research and ultimately contributed to the development of outputs that better met the needs of stakeholders.
- A case-by-case balance needs to be sought by individual researches to strike a balance between establishing and maintaining credibility and legitimacy and meaningful engagement that allows for co-development. Providing outputs that

are too preliminary comes with the risk of the researcher being perceived to lack credibility whilst delaying the sharing of intermediate outputs reduces the potential for co-development.

- Conversations regarding thresholds of acceptable and/or tolerable levels of risk are difficult to engage in, especially without concrete examples that are drawn from the local decision context and are grounded in existing levels of risk.
- Scenario-based pathways assessment is a powerful tool that allows for a dynamic consideration of risk. This is a particular advantage of a pathways based approach as the visualisations can be used to readily facilitate conversations about alternate futures in a way that is tangible for stakeholders.
- Physical scientists have a unique role to play in adaptation planning, ensuring that the best available science can be presented to decision makers in a way that is both accurate and digestible. Adaptation remains a fledgling field of practice, with the potential for significant innovation in the ways that we plan for a deeply uncertain future, and how we communicate those plans to decision makers and the broader public. This requires meaningful partnerships between the science and decision making communities.

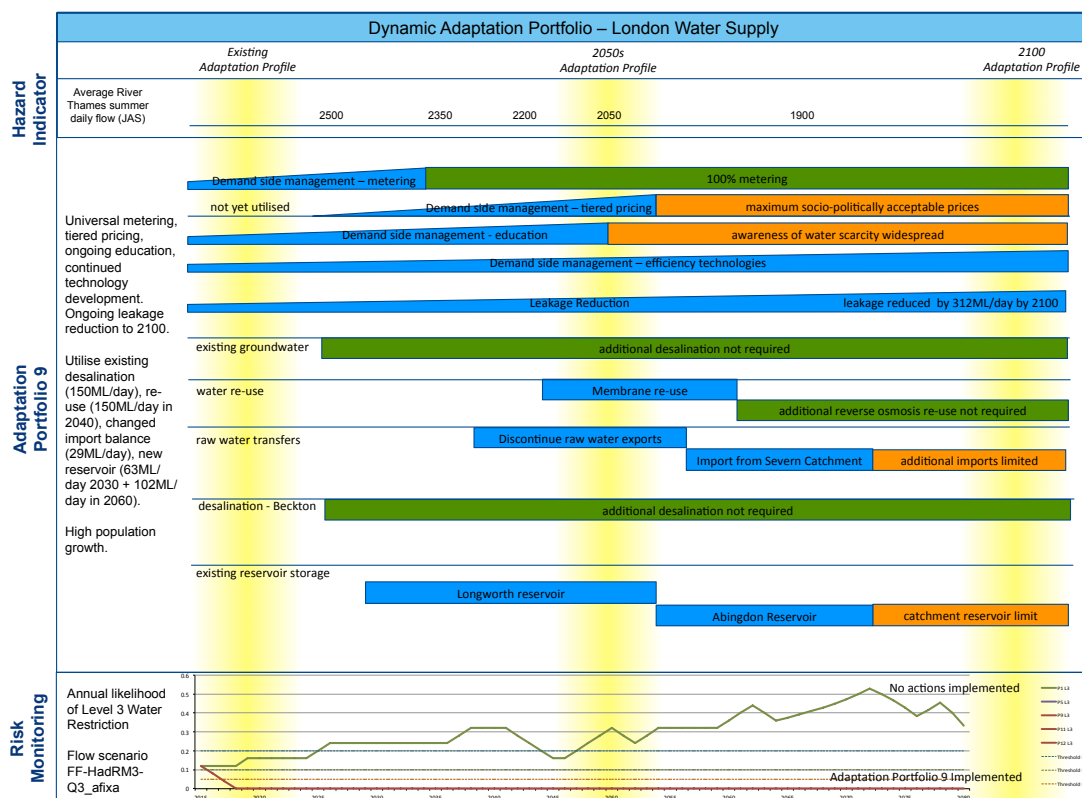


Figure C-1 Early version of an adaptation pathway diagram in response to water supply risk in London presented to Thames Water and the London Climate Change Partnership to help communicate potential benefits of a pathways approach

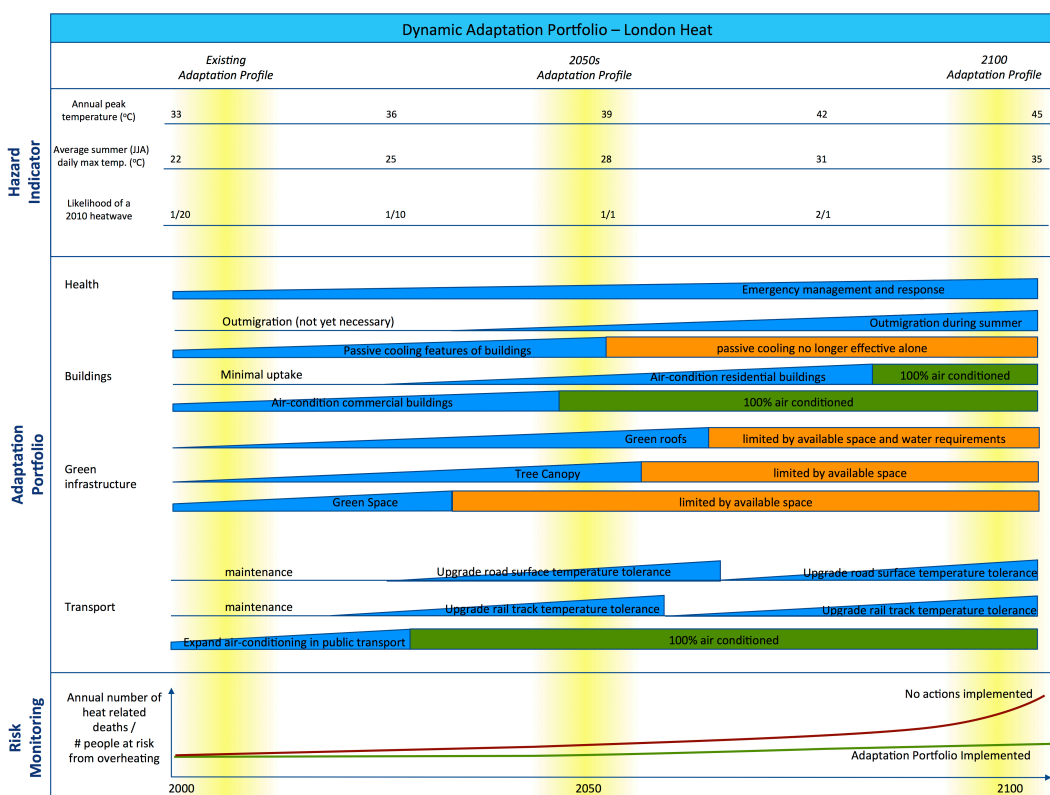


Figure C-2 Early version of an adaptation pathway diagram in response to heat risk in London, presented to the London Climate Change Partnership to help communicate the potential benefits of a pathways approach.

Principles for overcoming adaptation challenges

From a broader adaptation planning perspective a number of principles for overcoming challenges in adaptation planning were developed as part of this research. These have been derived from the adaptation planning literature and observed through participation in the adaptation initiatives described in this thesis.

- Successful planning for adaptation requires supportive and adaptive institutions (Huntjens et al., 2012, Pahl-Wostl, 2009, Eriksen et al., 2011, Füssel, 2007).
- Formal and informal partnerships, such as the London Climate Change Partnership and the London Working Group on Heat Risk, are an effective tool for bringing together diverse stakeholders (including representatives from Government, Academia, Non-Governmental Organisations and the Private Sector) who have a shared interest in mainstreaming adaptation.
- Vulnerability to existing climate variability should be identified and where possible addressed before considering future risks (Wilby and Dessai, 2010, ASC, 2010, Hallegatte, 2009, Füssel, 2007).
- Priority adaptation actions identified in response to existing vulnerabilities should be flexible, short-term and robust (Wilby and Dessai, 2010, Huntjens et al., 2012, Hallegatte, 2009). Where long-lived actions are identified, actions that are robust across a range of future scenarios should be prioritised (Hallegatte, 2009).
- Adaptation pathways should seek to maximise flexibility within a system and minimise sensitivity to climate change scenarios by delaying decisions until critical thresholds are realised (Haasnoot et al., 2013).

- Monitoring and evaluation is essential for understanding when thresholds are being approached and when additional adaptation actions need to be implemented to ensure an adaptation plan does not fail (Walker et al., 2013).
- Stakeholder participation is a key element of any successful decision making process (Huntjens et al., 2012, Pahl-Wostl, 2009, Eriksen et al., 2011).

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