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This paper introduces a framework for adaptation planning in urban water supply systems that links existing risk-based decision-making with the development of long-term adaptation pathways. We present a quantified assessment of how the risk of water shortages in London is predicted to vary dynamically through to 2100 depending on the choice of adaptation pathways and under different long-term transient population and climate scenarios. This approach helps to reconcile multiple decision timescales and demonstrates the value of strategic long-term adaptation planning to stakeholders by outlining long-term futures that may influence medium-term decision-making. Adopting a flexible approach to adaptation will be critical to the management of risk under uncertainty. This adaptation pathways approach demonstrates an effective framework for informing such decision processes.

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

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Abstract

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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 water supply risk. 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 (Hall et al. 2012c; Hallegatte 2009). Such decisions will contribute to enhanced water security, flexibility and robustness; or adversely, reduced resilience, mal-adaptation and undesirable lock-in (Ranger et al. 2010). Their importance makes overcoming the barriers to adaptation faced by resource managers crucial (Barnett et al. 2015; Hallegatte 2009).

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 (Nakhlooda et al. 2013; Walker 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 climatic and non-climate risks are inter-

1 related (Brown et al. 2012; IPCC 2012; Nazemi et al. 2013). Policy-first approaches are effective in
2 incorporating stakeholder input (Ranger et al. 2010). Risk-based approaches are suited to the
3 management of well-characterised uncertainties (Hall et al. 2012a). Robustness based approaches
4 can be difficult to apply in the development of dynamic long-term plans (Walker et al. 2013), but it is
5 important that any approach considers the robustness of near-term decisions that have long-term
6 implications given the deep uncertainties surrounding future climate and socioeconomic change
7 (Ben-Haim 2006; Hall et al. 2012b; Hallegatte 2009; Lempert and Schlesinger 2000; Wilby and
8 Dessai 2010).

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

35 Risk and vulnerability assessments are increasingly recognised as complimentary processes.
36 Adaptation frameworks, such as the one developed by Wilby and Dessai (2010), that combine top-
37 down and bottom-up assessments can leverage the advantages of both (IPCC 2012; IPCC 2014).
38 Pathways approaches should explicitly recognise and respond to existing management practices,
39 which decision makers are familiar with and may have a legislative requirement to fulfil (Brown et al.
40 2011), to more fully capture the benefits of considering near and long-term planning horizons.

48 A pathways approach was first applied as part of the Thames Estuary tidal flood risk management
49 project in London (Ranger et al. 2010). Adaptation pathways allow for a broad framing of the
50 adaptation decision problem and have subsequently been used in a range of contexts (Barnett et al.
51 2014; Haasnoot et al. 2013; Haasnoot et al. 2012; Lawrence et al. 2013; Rosenzweig and Solecki
52 2014; Siebentritt et al. 2014; Wise et al. 2014). Pathways approaches show significant potential for
53 contributing to long-term adaptation planning (Barnett et al. 2014; Haasnoot et al. 2012; Lawrence

et al. 2013; Park et al. 2012; Rosenzweig and Solecki 2014; Wise et al. 2014); 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 (Barnett et al. 2015; Haasnoot et al. 2012; Wise et al. 2014).

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 with the development of long-term 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 predicted 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. Section 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 5 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 6.

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

1 abstraction from the Rivers Thames and Lee and, to a lesser extent (approximately 20%),
2 groundwater sources. Furthermore, a 150 Ml/day desalination plant and reserve aquifers can be
3 activated to supply water to London during times of drought. Water supply in London is managed
4 by four private water companies, and regulated by the Environment Agency and the water supply
5 regulation authority. This study focuses on the London Water Resource Zone (LWRZ), which
6 includes 85% of London's residents. The LWRZ was chosen as it has been extensively studied,
7 data for quantitative analysis is available (Wilby and Harris 2006), and the technical and
8 institutional challenges being faced are representative of those being addressed across London.
9 London has been classified as a water-stressed city and already faces water scarcity challenges
10 (EA 2013). In March 2012, water restrictions came into force across London as two consecutive dry
11 winters caused very low levels in the River Thames and exceptionally low groundwater (GLA 2012).
12 The water restrictions were lifted in April, when exceptional rains terminated the prolonged drought
13 (Parry et al. 2013).

14 Climate change projections for the area suggest that by 2040 summer river flows and annual
15 rainfall may decrease whilst temperature may increase (Diaz-Nieto and Wilby 2005; Murphy et al.
16 2009). Overall water demand is expected to rise due to population growth and increasing single
17 household occupancy (HM Government 2012). Significant investment in water resource
18 management is anticipated this century to maintain the existing levels of supply reliability and
19 account for population growth and climate change (LCCP 2012).

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

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

3 Methodology

Stakeholder consultations informed the development of our adaptation pathways and framework for integrating risk assessment and adaptation planning. Our framework (Figure 1) is risk-based and iterative, prioritises management of existing risks, and guides the development of long-term adaptation pathways. We consider adaptation pathways to be complementary to existing near and medium-term decision-making approaches and not a replacement for two main reasons. Firstly, in contexts where existing risk is not well managed, it is important to prioritise the management of risks from existing climate variability before committing scarce resources to long-term planning (Wilby and Dessai 2010). Secondly, stakeholders are less restricted by existing institutional, legal and financial constraints when contemplating long-term planning horizons. This helps to facilitate creative consideration of a broader range of climatic, technological and institutional futures (Wilkinson and Kupers 2014).

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.

Figure 1 Integrated framework for risk assessment and adaptation planning.

3.1 Review

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

3.2 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 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.

3.4 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.

3.5 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 the present value cost of implementing each pathway to be calculated. 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.

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.

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 managing 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 interest in understanding the potential for adaptation pathways to be used in adaptation planning for water resources in London.

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 (Environment Agency 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 2011; GLA 2012).

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 2011). 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.

The adaptation canvas provided the solution space from which six dynamic adaptation portfolios of actions were derived. Figure 2 shows the adaptation canvas developed for the LWRZ, highlighting

pathway 5, the mixed portfolio of supply and demand options in blue as a pathway for illustrative purposes. 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 term of reduced demand or increased supply. The limits of each action were illustrated in the canvas as a potential contribution to the overall supply demand balance, this also formed the basis of the later consideration of the overall limits to adaptation at the system scale.

Figure 2 Adaptation canvas for London's water resources, highlighting Adaptation Pathway 5.

4.3 Adaptation portfolios

Six portfolios of actions were identified in consultation with stakeholders from TW, 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 1.

Table 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/d in 2100, utilise existing desalination (150ML/day))	Moderate demand management (per-capita demand reduced to 150 L/p/d, leakage reduced to 422 ML/d by 2100, utilise existing desalination (150ML/day))	Medium demand management (per-capita demand reduced to 130 L/p/d leakage reduced to 422 ML/d 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/d 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/d in 2100, utilise existing desalination (150ML/day))	Moderate demand management (per-capita demand reduced to 150 L/p/d, leakage reduced to 422 ML/d by 2100, utilise existing desalination (150ML/day))	Medium demand management (per-capita demand reduced to 130 L/p/d leakage reduced to 422 ML/d 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/d 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).

4.4 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. 2012c). 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 recognized that 100% reliability of supply is not possible. Based on the frequency of shortages users will tolerate and their willingness to pay to reduce the frequency of shortages, water utilities establish planned frequency of water use restrictions for shortages of varying levels of severity, as per Table 2. Tiered water-use

restrictions are introduced to reduce demand and hence the likelihood of further restrictions becoming necessary.

Table 2 Target frequency of water restrictions in the LWRZ (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.

4.5 Appraisal and visualisation

A transient version of the UKCP09 Weather Generator 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. 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).

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 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. A 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).

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.

5 Results

We have defined risk as the probability of exceeding the target frequency for water use restrictions. Figure 3 shows 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 Figure 3. 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). Stakeholder consultations indicated that there is no desire to increase the level of risk within the system, but existing levels of risk are acceptable, 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 Risk-based appraisal of the effectiveness of Adaptation Pathways 1–6.

Without further investment (Pathway 1 - black line in Figure 3), 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. 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

1 that could be mal-adaptive. There is a high degree of uncertainty regarding the effectiveness
2 of demand management actions. A pathway that increases the reliance on per-capita demand
3 reduction must place a high priority on monitoring the outcomes of adaptation action in
4 reducing demand. A lack of progress in reducing demand up to 2030 may indicate that
5 pathways that rely significantly on demand reduction need to be reconsidered; alternatively
6 successful demand reduction may prompt consideration of pathways with even more
7 aggressive demand reduction.
8
9

10 Stakeholders identified that strategic decision-making is most strongly influenced by low
11 frequency high consequence events – an ‘emergency drought order’ currently has a target
12 frequency of ‘never’ (Thames Water 2014). We adopted a target frequency of failure of 1 in
13 1000 years in our analysis to reflect the significant implications of an emergency drought
14 order on individual customers and strategically for London. From a London perspective, this
15 provides consistency with the design return intervals for its estuarine flood defences. Our
16 analysis identified Pathways 3–5 as capable of keeping the probability of exceeding the target
17 frequency of an emergency drought order below 0.01, through to 2100 under a medium
18 emissions scenario.
19
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21 Costing is an important consideration in identifying trade-offs for adaptation decision-making.
22 The present value (PV) cost of the actions included in Pathways 1–12, for a range of discount
23 rates, was calculated to provide an initial estimate of the relative cost of each pathway, as per
24 Table 3. The costs are in addition to the existing costs of managing the system. The PV
25 includes capital and operational expenditure and is dependent on the specified level and
26 timing of investment.
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29 Under a high population growth scenario Pathways 3–5 are most effective in managing risk. A
30 supply side prioritisation portfolio is more expensive than moderate demand management or
31 a mixed portfolio with a discount rate of 4.5%. It is less expensive however, with a lower
32 discount rate of 3.5% or 2.5%. This change in ranking highlights the sensitivity of the
33 decisions to discount rates and further investigation is suggested (Mortazavi-Naeini et al.
34 2014).
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Table 3 Present value cost estimate of Pathways 1–12 (2015-2100).

Additional Investment – PV (£ millions)						
Discount Rate	4.5%	Rank	3.5%	Rank	2.0%	Rank
Pathway 1	£ -	1	£ -	1	£ -	1
Pathway 2	£ 371	2	£ 507	2	£ 879	2
Pathway 3	£ 439	5	£ 620	6	£1,129	6
Pathway 4	£ 444	6	£ 586	4	£ 929	4
Pathway 5	£ 437	4	£ 609	5	£1,074	5
Pathway 6	£ 392	3	£ 536	3	£ 900	3
Pathway 7	£ -	1	£ -	1	£ -	1
Pathway 8	£ 309	2	£ 422	2	£ 729	2
Pathway 9	£ 416	4	£ 585	4	£1,059	6
Pathway 10	£ 444	6	£ 586	5	£ 928	4
Pathway 11	£ 429	5	£ 596	6	£1,048	5
Pathway 12	£ 392	3	£ 536	3	£ 900	3

The development of long-term adaptation pathways is presented as an iterative process, as per Figure 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.

Figure 4 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 4 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 4 Adaptation pathways for water resource management in London.

6 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. A long-term plan reduces the likelihood of mal-adaptation and undesirable lock-in, creates

1 awareness of the dynamic nature of the climate system, and builds the political and business
2 case for integrating flexibility into infrastructure planning (Ranger et al. 2013).
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5 The aim of this study has been to demonstrate an adaptation pathways method that may
6 inform adaptation planning for London's water resources, rather than develop London's long-
7 term water resource management plan. The development of London Water 2100 or an
8 equivalent long-term plan would require more extensive consultation and the consideration of
9 a broader range of perspectives and decision criteria. Initial stakeholder feedback found the
10 pathways diagrams to be a potentially valuable input to long-term planning.
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18 We used multiple versions of pathways diagrams to present quantified transient scenarios
19 outlining the trade-offs between risk and investment in adaptation actions to facilitate
20 conversations about different futures, Pathways 3 and 4 are included in Figure 5.
21 Stakeholders found that our method created a 'free thinking space' for the unrestricted
22 consideration of actions that may not be politically or financially acceptable in the near-term.
23 In this thinking space, the implications of prioritising flexible actions as a means of achieving
24 robust outcomes can be explored in focus group discussions. Pathway 3, for example, is
25 more flexible than a portfolio consisting of two new reservoirs and a re-use plant (Pathway 4),
26 but it is more expensive.
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37 An adaptation plan is considered robust if it performs adequately across a broad range of
38 plausible climate, population and investment scenarios (Wilby and Dessai 2010). Considering
39 portfolios of actions provides the flexibility to cope with a variety of possible future conditions
40 and can help to compensate underperformance of any particular action. A pathways
41 approach contributes to the development of dynamically robust plans by incorporating
42 flexibility in the scheduling and implementation of actions, and allowing changing levels of risk
43 to inform future decisions.
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Figure 5 Adaptation pathways 3 (left panel) and 4 (right panel) for water resource management in London.

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 (Environment Agency 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.

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

1 stakeholders indicated that further understanding of the implications of varying acceptable
2 and tolerable levels of risk is required. Future pathways research could utilise optimisation
3 approaches to identify the pathways that perform best for the specified input assumptions
4 across a range of risk thresholds (Beh et al. 2015; Matrosov et al. 2015; Mortazavi-Naeini et
5 al. 2014). Better understanding the implications of varying threshold levels is also valuable as
6 threshold levels of risk vary according to stakeholders' values (Haasnoot et al. 2012).
7 Furthermore, risk thresholds are likely to evolve in the future depending, in part, on how
8 severe future water shortages are, on how these risks compare with the costs of adaptation
9 (Hall and Borgomeo 2013; Wade et al. 2013; Yohe and Leichenko 2010).

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

1 This study has demonstrated an innovative approach to the development of adaptation
2 pathways that responds to increasing water supply risk. We have quantified how risk varies
3 dynamically for a range of adaptation pathways through time with climate change and
4 population growth and we have demonstrated how transient probabilistic climate change
5 projections can be used to extend water resource planning horizons to 2100.
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10 Future water resource decision-making will continue to be a process of managing trade-offs in
11 a complex dynamic risk landscape, and implementing actions as necessary to manage water
12 supply risk. The implementation of these actions through time will result in an adaptation
13 pathway. London's ability to remain a world-leading city in an increasingly globalised
14 economy is dependent on it being an efficient and low risk place to do business and desirable
15 place to live. London and cities internationally will increasingly need to develop and
16 implement adaptation strategies that consider multiple long-term climate risks. This
17 adaptation pathways approach demonstrates an effective framework for informing such long-
18 term adaptation planning.
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*Highlights

- A framework for adaptation planning in urban water supply systems is proposed.
- Existing risk-based decision-making links with development of long-term adaptation pathways.
- Approach helps to reconcile multiple decision timescales.
- Outlines long-term futures influence on near-term decision-making to demonstrate value to stakeholders.
- A flexible approach to adaptation is critical to the management of risk under uncertainty.