Adaptation pathways for infrastructure operators and policymakers

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Infrastructure operators must adapt to a range of hazards associated with climate change including sea level rise, increased frequency of extreme weather events such as heavy rainfall and heatwaves, and gradual climatic change that may leave assets operating in day to day conditions different to those which they were designed for. Adaptation pathways can be described as a "sequence of actions, which can be implemented progressively, depending on future dynamics" (Werners et al 2021) in order to assist adaptation to climate change. The development of adaptation pathways can assist infrastructure owners and operators to adapt their existing assets and networks to maintain desired operational performance under future as yet unknown climate (and e.g. socio economic, policy) conditions.

Adaptation pathways provide a flexible framework to consider future climate change and other socio-economic uncertainties for a range of business operations including infrastructure design, asset repair and management, business continuity, emergency response, or supply chain management. The pathways approach considers multiple adaptation options for a range of climate scenarios, including high-end low-probability climate change. The adaptation options identified are then sequenced in different pathways, considering other factors such as biodiversity or urban development. Multi-criteria decision-making analysis or similar processes are used to select the current preferred pathway and environmental indicators such as sea-level rise determine when adaptation activities need to switch to a different pathway.

Adaptation pathways were pioneered in the UK as part of the Environment Agency TE2100 project to manage flood risk along the Thames Estuary, including London, until 2100 (Ranger et al., 2013). More recently, they form part of the Thames Water Resource Management Plan (Thame Water, 2019). In both these examples, high-end climate change scenarios were combined with sophisticated industry modelling, risk analysis, and decision-making processes in order to support strategic investment in critical infrastructure assets. Such resource intensive inputs to the development of Adaptation Pathways are not always necessary, Somerset County used a contrasting approach in terms of modelling input (Trioss, 2019) where Rapid Adaptation Pathways Assessments for coastal erosion and flooding were developed via a workshop that brought together infrastructure operators, the local authority, Environment Agency, Wildlife Trusts and others. The process quickly outlined interdependencies, immediate actions, future opportunities, and long-term actions to be funded in the future. Moreover, the value of adaptation pathways and thresholds are recognised at County level, and local councils (e.g. Wedmore Parish Council) are creating their own adaptation pathways.

Adaptation pathways are widely advocated by academic and practitioner communities as an adaptation approach that considers the inherent environmental and socio-economic uncertainties of climate change. An increasing amount of resources are becoming available to support infrastructure operators and policy makers to design and implement adaptation pathways. The TE2100 project created a nine-step process to develop climate change adaption pathways, and there are multiple framework and exemplar adaptation pathway methodologies from academic and practitioner communities (Reeder and Ranger, 2011; Quinn et al., 2018). In 2019, International Organisation for Standardisation (ISO) released the first international standards for managing the impact of climate change, and the British Standards Institution is drafting a guide to specifically support the application of adaptation pathways. The evidence base for the benefits and effectiveness of the adaptation pathways approach is limited to a few case studies such as TE2100 and the Dutch Delta Programme (See Section 1.2). However, practitioner feedback is generally positive. Challenges include addressing the complexities of determining thresholds/tipping points for hazards with large natural variability, providing clarity over who is financially responsible for decisions and associated impacts, including a broad range of options in the pathways, and ensuring the options include longer-term transformative actions rather than focusing on more easily achievable short-term objectives (Wise et al., 2014; Lin et al., 2017; Bloemen et al., 2018).

1. Introduction to Adaptation Pathways

1.1 Context

Global warming is changing weather patterns, often increasing the frequency and magnitude of extreme weather events such as heavy rainfall, and causing sea level rise (IPCC, 2013). Climate projections show that the UK: is expected to become warmer by the end of 2100, particularly in summer, and hot summers will be more likely; extreme rainfall events will become more frequent with significant increases in hourly rainfall amounts; and, sea level is rising, more so in the south than in the north (UKCP, 2019). For infrastructure operators, a long-term gradual change in climate may lead to infrastructure assets operating in a different climate (e.g. hotter or drier) to which they were designed. Sea level rise will reconfigure the coastline, increasing the risk of coastal flooding, and in some cases forcing the relocation of assets. Moreover, extreme weather events can causes serious damage and disruption to UK infrastructure, including disruption caused by heat or heavy rainfall to railway services (Dawson et al., 2016; Ferranti et al., 2018), loss of power supply (e.g. Lancaster lost power for two days following rainfall from Storm Desmond; Ferranti et al., 2017), and widespread flooding (e.g. winter of 2013/14; Brown et al, 2014).

It is therefore imperative that infrastructure owners and operators and policy makers adapt to climate change, to reduce the damage and disruption caused by extreme weather or coastal flooding and to ensure the operability of their infrastructure in a future climate. This is particularly important for infrastructure with a multi-decadal lifespan, such as reservoirs or structural assets such as tunnels, bridges, track, or underground pipes. In order to adapt to climate change, infrastructure operators and policy makers must incorporate an uncertain future climate with uncertain future impacts alongside future socio-economic uncertainties within decision-making for infrastructure design, asset repair and management, business continuity, emergency response, supply chain management, or other business operations. Adaptation pathways provide a flexible framework to incorporate these future uncertainties and enable climate adaptation.

1.2 Adaptation Pathways

Adaptation pathways are a series of interlinked and flexible options for climate adaptation that combine long-term adaptation plans for a range of climate scenarios with short-term objectives and actions (Ranger et al., 2013; Haasnoot et al. 2019). Within an adaptation pathways framework (Figure 1), decision-makers have the flexibility to include new information as it becomes available, and change the course of adaptation (i.e. switch pathway) if required. Environmental indicators, such as sea-level rise or frequency of flood events can be used to inform decisions when to switch between pathways. Adaptation pathways have their root in adaptive management (Walker et al., 2001), and have been developed by several academic-practitioner groups, each using a slightly different terminology and approach (Table 1). Adaptation pathways have been developed for a range of sectors such as irrigation (e.g. Nikkels et al., 2019), food production (Tanaka et al., 2015), the conservation of biodiversity and cultural heritage (Jacobs et al., 2019). Exemplar adaptation pathways from the infrastructure sector include:

- **Thames Estuary:** The TE2100 project (Section 2.1), pioneered the adaptation pathways approach for coastal flood risk management. A similar approach was applied to London's water supply (Kingsborough et al., 2016) and heat-risk (Kingsborough et al., 2017), but these did not translate into policy (Section 3).

- **Dutch Delta Programme:** This is a collaboration between national, regional and municipal governments, and water boards to improve flood risk management and reduce the vulnerability of water supply in Netherlands. It uses Dynamic Adaptive Policy Pathways (DAPP) and Adaptation Tipping Points (ATP) (Kwadijk, et al., 2010; Hasnoot et al., 2013; Hasnoot et al., 2019; Figure 1). The 2100 adaptation.

- **Australia:** local government and community groups co-created adaptation pathways to manage sea level rise within the township of Lakes Entrance in South-Eastern Australia (Barrnett et al., 2014; Figure 3). Here, the prevailing approach to adaptation typically restricted development, which was often opposed by local residents. However, by co-creating an adaptive approach to identify no and low-regret solutions a socially-acceptable framework was produced for local residents. Stakeholder engagement was a major part of adaptive planning on the Eyre Peninsula, South Australia, for several different decision areas, including road infrastructure, coastal development, peri-urban expansion, and water resources (Siebentritt et al., 2014).

1.2 Adaptation Pathways

- **New York City:** the New York City Panel on Climate Change created an adaptation framework for climate mitigation and adaptation focused on coastal flooding (Rosenzweig et al., 2011). Adaptation pathways initially focussed on preventing disruption to current systems, but following damage caused by Hurricane Sandy in 2012 (costing > US$19 billion), which took the level of risk to an unacceptable level (Figure 2), these evolved into pathways to deliver regional transformative change (Rosenzweig and Solecki, 2014).

- **California:** The Adapting to Rising Tides project (Nguyen et al., 2011), used Dynamic Adaptive Plans to protect transport infrastructure, in the San Francisco Bay area including the Capitol Corridor intercity rail route from different levels of climate change and associated sea-level rise (Wall et al., 2015). Adaptation pathways have also been developed for sea level rise along the Los Angeles coast (Aerts et al., 2018).

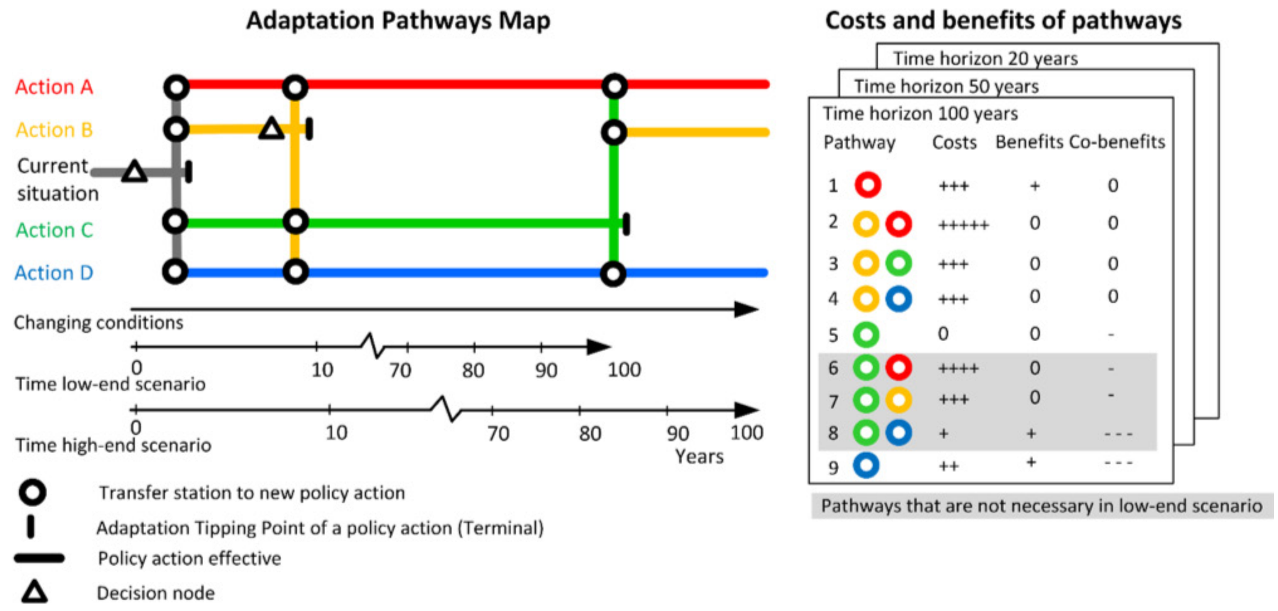


Figure 1: An example of a simplistic adaptation pathways map, with a scorecard for each adaptation option taken from Deltares1. Here, there are four options for adaptation, A, B C, and D. Options A and D enable objectives to continue to be met for approximately 100 years under both low and high end climate impact scenarios, while Option C works for 100 years under the low-end scenario. Action B would only enable targets to be met for a further 10 years after which an Adaptation Tipping Point would be reached (e.g. floods repeatedly overtopping defences), prior to that a decision would need to be taken of which alternative action to take next. Each option has different costs and benefits.

Table 1: Overview of the terminology often used to describe the adaptation pathways approach by different groups of researchers and practitioners.

Terminology	Definition
Adaptation Pathways approach	A flexible approach or framework that combines several different pathways for climate adaptation that can change over time as new information becomes available (e.g. improved climate projections) or if environmental triggers indicate a pathway switch is required (e.g. Rosenzweig et al., 2011; Reeder and Ranger 2011). Sometimes referred to as decision pathways.
Adaptation Tipping Points	"Points where the magnitude of change due to climate change or sea level rise is such that the current management strategy will no longer be able to meet its objectives. This gives information on whether and when a water management strategy may fail and other strategies are needed" (from Kwadijk, et al., 2010). A specific term used as part of Dynamic Adaptive Policy Pathways (DAPP) developed by Deltares1 and TU Delft used on the Dutch Delta Programme.
Adaptive Policies	Policies that respond to changes over time and that make explicit provision for learning (from Walker et al., 2001).
Deep Uncertainty	A way to describe the deepest uncertainties associated with future climate, i.e. what we don't know that we don't know (e.g. Ranger et al., 2013; Wall et al., 2015), or a "black swan" event (after Taleb, 2007).
Dynamic Adaptive Policy Pathways	Also known as DAPP. A specific term used to describe dynamic adaptive planning using the approach developed by Deltares and TU Delft used on the Dutch Delta Programme (e.g. Kwadijk, et al., 2010; Haasnoot et al., 2013).
Dynamic Adaptive Planning	The development of an adaptation plan, that identifies and guards against vulnerabilities, with signposts to monitor the uncertain vulnerabilities, that has an interlinked implementation plan, that can respond and change as indicated by the signposts (Wall et al., 2015). Also known as iterative risk management, dynamic robustness, or managed adaptive (for more details see Ranger et al., 2013).
Environmental Trigger / Signposts / Thresholds	The type of information that should be tracked to inform a switch (or not) to a different adaptation pathway (e.g. Ranger et al., 2013). Also see Adaptation Tipping Points.
Route map	The diagram showing the different adaptation pathways (or decision pathways)

The overarching principle of adaptation pathways is that climate adaptation cannot be solved by a single action, at a single point in time, but instead is a process that must be updated and managed over time as information becomes available and in response to environmental and socio-economic changes (Barnett et al., 2014). Within the different approaches and academic-practitioner groups outlined in Section 1.2, there are several common subprinciples (after Wise et al., 2016) listed below.

- **Flexibility;** using adaptation pathways introduces flexibility and options into the decision-making process by providing multiple options for adaptation for multiple future climate and socio-economic scenarios, whilst maintaining a robust and systematic structure to support decision-making.
- **Learning** underpins the process and regular/iterative reviews or reassessments is fundamental to the pathways approach to incorporate new information such as updated climate projections, socio-economic changes, or other new understanding.
- **Environmental Indicators,** also referred to as thresholds, Adaptation Tipping points, or triggers, are embedded within the pathways to denote when a management strategy is no longer viable and a different adaptation strategy must be adopted (Figure 1). This contrasts with using arbitrary time periods to switch to different pathways (e.g. 5 years), that have no basis in the likelihood of environmental risk.
- **Decision-orientated (or decision-centric;** Ranger et al., 2013): adaptation pathways focus on the decision to be made, not on the science of climate change, or a geographic region, or arbitrary time periods.
- **Avoiding maladaptation:** a pathways approach considers the “worst-case scenario”, and solutions for this at the outset, to prevent costly retrofitting or maladaptation in the future, combined with;
- **Low and no regret actions,** which can be incorporated now or in the future (although an overt focus on small incremental changes can deter larger transformational changes that may be required for long-term adaptation; see Section 3).
- **Communication and discussion tool:** the adaptation pathways approach is a useful framework to explore and communication adaptation with the context of uncertainties, and can provide a useful visualisation tool to communicate complex science and ideas to multiple audiences.

- **Acceptable (or unacceptable) levels of risk:** the pathways are constructed around what represents an acceptable or unacceptable level of risk, i.e. a pathway switch is required when the level or risk is no longer considered acceptable, as defined by an environmental indicator (Figure 2). The acceptable level of risk will vary dependent upon stakeholder perspective (Barnett et al., 2014); for example, a home/business owners will want their property protected from coastal erosion, but this may not be cost-effective from a local authority perspective. The level of acceptability can also change, for example following an extreme weather event such as Hurricane Sandy (Rosenzweig and Solecki, 2014). Acceptability can be determined by multi-criteria analysis or other decision-making techniques.

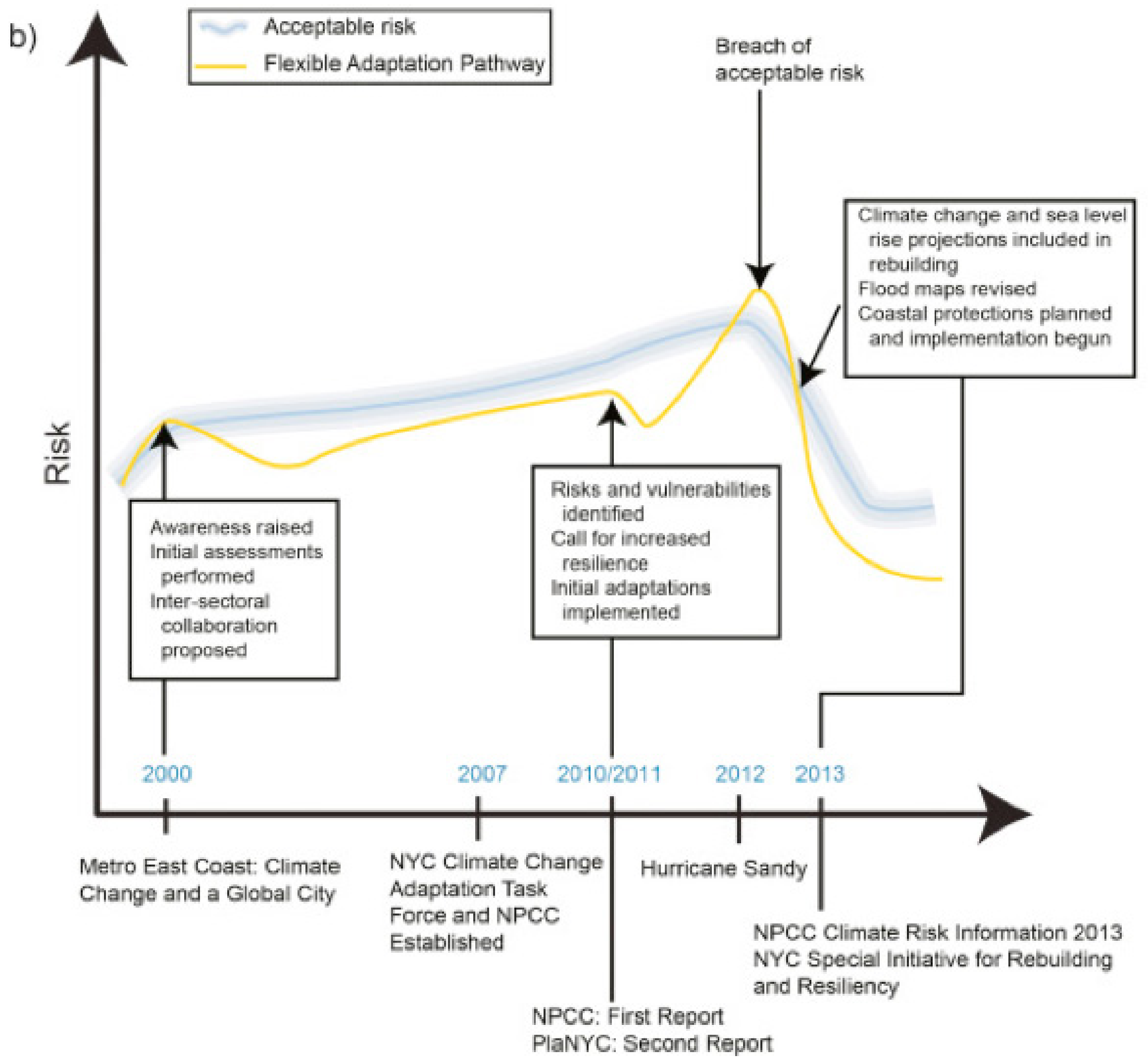


Figure 2: A timeline of a Flexible Adaptation Pathway showing key milestones, and the relationship to socially acceptable level of risk in the New York metropolitan region, 2000–2014. From Rosenzweig and Solecki (2014).

2. Case Studies of Adaptation Pathways for Infrastructure Adaptation

This section contains four examples of adaptation pathways for infrastructure operators in the UK. It contrasts the very detailed exemplar of the TE2100 project (2.1), the application of Rapid Adaptation Pathways Assessments in Somerset County (2.2), and two different approaches to adaptation pathways to manage water resources in London (2.3 and 2.4). It shows how a pathways approach can be used by different organisations with different levels of financial resource and levels of preparedness to support climate adaptation for different climate challenges.

Table 2: The three steps used by the TE2100 project to develop adaptation pathways for the Thames Estuary. For more details see Reeder and Ranger (2011) and Ranger et al. (2013).

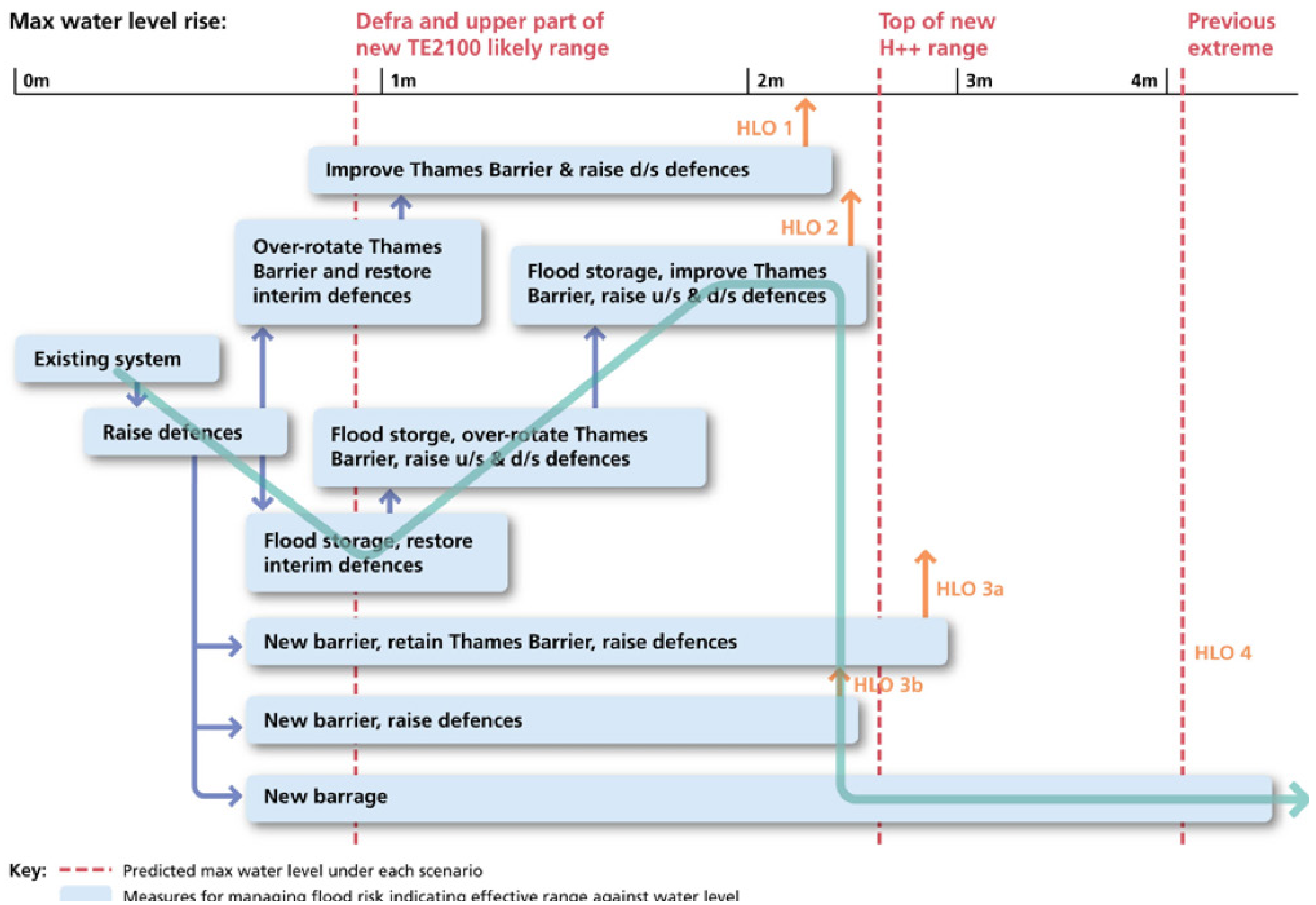
Step One Structure	i Address the current vulnerability of the system in order to understand existing protection and flood risk. Ii Map the future sensitivities to climate change and other risks, including considering high-end climate change (e.g. Wade et al., 2015), in this case, a maximum potential sea level rise of 4.2m was initially considered. This was subsequently revised to 2.7m later in the project following a new modelling study. iii Assess the key thresholds (such as level or walls, embankments and the performance of the Thames Barrier) between the current vulnerability and maximum sea-level rise. iv Identify different adaptation options at a high level to respond to these thresholds (shown in Figure 4). v Check interactions between the adaptation options and other issues such as ecosystem impacts or urban development at the macroscale vi Create the different adaptation pathways that address the different thresholds. These are referred to as High-Level Options (HLOs) in Figure 4.
Step Two Appraise Solutions	vii Compare costs, benefits and other criteria such as environmental impact for the different adaptation options (HLOs). TE2100 used a multi-criteria approach consistent with the Environment Agency's Flood and Coastal Risk Management Appraisal Guidance (EA, 2010) viii Recommend the pathway along with the key variables / indicators that will need to be monitored to determine when a threshold (or tipping point) will be exceeded, and the pathway should change. Indicators include: relative (mean) sea level rise; peak surge tide level and wave heights; peak river flood flows; condition of flood defences; flood barrier reliability (and closure frequency); developed area and value; extent of erosion and deposition; intertidal habitat area; land-use planning and new developments and public/institutional attitudes to flood risk
Step Three Implementation	ix Implement the adaptation pathway and monitor the different indicators to inform whether the pathway continues to provide sufficient flood risk management, or whether it should be revised.

2.1 Thames Estuary (TE2100): flood risk (storm surge) management on a coastal estuary

The Thames Estuary (TE2100) project pioneered the use of pathways for climate change adaptation (Ranger et al., 2013). The project addressed flood risk in London and the Thames Estuary until 2100, including whether the Thames Barrier, could provide long-term protection from storm surges given global sea level rise (Reeder and Ranger, 2011). The adaptation pathways were considered within the context of future land use planning, the social, cultural and commercial value of the Thames Estuary, and how estuarine ecosystems could be enhanced and restored to improve biodiversity and maximise the benefits of natural flood events for the environment (EA, 2012). Table 2 shows the three-step process used during the TE2100 project, while Figure 3 provides one of the outputs; for more details see Reeder and Ranger (2011) and Ranger et al. (2013).

By creating a sequence of adaptation measures the Thames Estuary has a flood risk management plan until 2100 that incorporates the uncertainty of climate change and considers other environmental (habitats and biodiversity) and socio-economic factors (e.g. land use changes, public/institutional risk perceptions). The adaptation plan was approved by Government, with a budget of £250 million for the first 10 years. The adaptation pathways map is scheduled to be reviewed and reappraised every 10 years, with a mid-term monitoring review of the indicators every 5 years.

Figure 3: The TE2100 route map showing the different adaptation options for different levels of sea-level rise. H++ refers to high-end climate change scenarios produced by the UK Met Office (Wade et al., 2015) High-Level adaptation Options (HLO) and pathways developed on TE2100 (on the y-axis) are shown relative to threshold levels increase in extreme water level (on the x-axis). The preferred route is shown by the blue line; decisions initially follow HLO2 and switch to HLO4 if needed (from Ranger et al., 2013).



2.2 Somerset: undertaking Rapid Adaptation Pathways Assessments for flood-risk management

Rapid Adaptation Pathways Assessments (RAPA) are a first step to developing an adaptive approach to climate change related risk management. Somerset is a low-lying coastal county that suffered extensive flooding during winter 2013-14 and considers itself to be susceptible to future flooding associated with global sea-level rise. The Council used a 2019 workshop convened by Trioss2 (Trioss, 2019), to bring together infrastructure operators, the local authority, Environment Agency, Wildlife Trusts and others, to discuss and undertake a RAPA for coastal erosion and flooding and another covering fluvial flooding. The participants considered: (i) the impact of high-end climate projections of sea level rise that project up to 2m rise in sea level alongside increases to fluvial peak flood flows (<100%) and surface flood levels (< 60%) by 2100 (Wade et al., 2015); (ii) the UKCP18 climate projections that indicate sea level rise of between 0.27m and 1.13m by 2100 (Fung et al., 2018); and flood maps showing the extent of 2013/14 floods, and future flooding projections for a 1m rise in sea level and 40% increase in peak flood flows prepared by the Environment Agency. Separate work groups were convened to consider: Coastal flooding; Fluvial flooding; Community Group Responses and other Non-Structural Responses, i.e. issues not related to physical infrastructure, such as planning, communication emergency and contingency, moving communities. Each group were asked to answer the following five questions:

1. What current plans would need to be revised for a sea level rise of 1m?
2. What plans would need to be revised for a sea level rise of 1-2m?
3. What interdependencies exist whereby one impact of flooding also threatens to disrupt other parts of Somerset life and so increases the impact?
4. What opportunities exist in Somerset as a consequence these climate change impacts?
5. What gaps in the evidence base require further investigation to improve decision-making?

Table 3 shows an extract from the qualitative responses that were collected during the RAPA, shown for Non-Structural and Community Group Responses. In Somerset, the value of the pathways approach is recognised at County level, and is being adopted in community engagement by Councils and others to develop responses to climate impacts (Trioss, pers. comm. Apr 2020; Figure 4, for RAPA for surface flooding for Wedmore). For example, incorporating mental health management within future flood resilience is now under consideration, and the Council are assessing the insurability and investability of different adaptation options with Trioss and Climate Wise, who support the insurance industry in responding to climate change. The Council are also developing adaptation plans for the eight strands of the Somerset Climate Emergency; communications and engagement, built environment, energy, farming and food, industry, business and supply chain, natural environment, transport, waste and resource management, and, water.

Non-Structural and Community Group Responses	
What current plans would need to be revised before for a sea level rise of 1m (threshold up to 1m)?	Many agencies have lost staff and resources with recent cuts. Services are not likely to be to the same level if there was a repeat of the 2013/14 floods today.
	As climate vulnerabilities increase, other parts of the country would be affected too, and so mutual aid systems from neighbouring counties would not be available
What plans would need to be revised before for a sea level rise of 1-2m (thresh-old between 1m-2m)?	At 1m sea level rise existing plans would be overwhelmed
	We are asked by Government climate projections to consider the reasonable possibility of a post 1m world but do not need to make decisions yet. In the time before decisions need to be made, a watch for the likely time when 1m sea level rise could be exceeded 50 years in the future needs to be kept. Projections for sea level rise have been increasing, so the possibility of going beyond 1m by the end of the century is also increasing, although it is currently not the most likely outcome. If it does not happen this century, it is very likely to happen next century.
	In the recovery phase following a flood, procurement policies in some agencies is currently replacing like for like. This is a barrier to transfer learning into practice about how to do things better into practice. To develop resilience up to the higher post 1m sea level rise scenarios, it will be essential to: - Learn from experience as well as future projections, and - Convert that learning into new practice how to either: 1. recover to the current “normal” after increasing levels of climate impact or 2. re-adjust to a “new normal” because practices for the current normal is are/will soon become no longer viable.
What opportunities: exist in Somerset as a con-sequence these climate change impacts?	Purchase strategy, there is an opportunity to purchase land for water storage.
	Develop the capacity of politicians and funders to support plans for a future that does not look like the past.
What gaps in the evidence base require further inves-tigation to improve deci-sion-making?	There are gaps in the understanding of the vulnerability of some key infrastructure e.g. in the high case scenario and climate change levels towards it, which are important to understand for Somerset’s resilience
	Where would rail and displaced communities go? What spaces need to be protected to allow that change if and when required?

Table 3: Exerts from the working group on Non-Structural and Community Group Responses (i.e. issues not related to physical infrastructure such as planning; communication; emergency and contingency; moving communities). Two or three responses have been selected for each sub-division of the table to illustrate the responses used to compile the adaptation pathways. The complete table is available in Trioss (2019) alongside similar tables produced by the other working groups.

Wedmore Rapid Adaptation Pathways Assessment (RAPA) - Surface Flooding & Town Management

Activity	Increased surface flooding flow					
	10%	20%	30%	40%	50%	60%
Drains cleared						
SuDs maintenance						
Domestic water butts						
Brooks committee	Review current infrastructure effectiveness and adaptation requirements					
Review current constitution		Are current roles and responsibilities sufficient for future flood management				
Widen brook						
Soak away - Mill Lane						
Soak Away - Hill						
Soak away - Manor Lane						
Review soak aways that aren't working						
Tree planting (slow the flow)	Plant now, benefit later					
Redirect brook back to natural path						
Ash tree replacement programme						
Aim to change planning rules	Make them climate smart e.g. existing development areas approved before current regs					
Increase water storage on levels						

Figure 4: The RAPA produced for Wedmore Parish Council, Somerset. Provided by Trioss.

2.3 Thames Water: Adaptive Pathways for water resource management and drought resilience

Thames Water is water supply and waste water treatment utility for 15 million customers in London and the Thames Valley. Their 2019 Water Resources Management Plan (WRMP, Thames Water 2019a; 2019b) considers future water resources until 2100, including measures to address forecasted supply demand deficits in the region, and increase resilience to severe drought. The WRMP includes an adaptive pathway to secure resilience to a 1 in 200 year drought event before 2030, and consider options for strategic water resource management in the long term (Thames Water, 2019a). Figure 5 shows adaptation pathways for four futures; aspiration, optimistic, expected, the drivers for which are shown in Table 4 and were determined by an adaptability analysis (Thames Water, 2019b). The adaptation pathway approach integrates climate change, alongside other sector challenges such as leakage, per capita consumption, and population growth.

The "expected future" is the preferred plan, and requires strategic regional resource (SESR) in 2037/38. At present, the precise thresholds that would indicate that Thames Water need to switch pathways away from the expected future are unknown, and are the subject of ongoing research and modelling (during the AMP7 period), which will feed into the decision point in 2022/3. In a more challenging future, strategic investment would be required earlier; for the optimistic and aspirational futures, the resource could be delayed. A decision (shown as "decision point" in the diagram) is required before 2022/3 to determine future strategic investment. The immediate investment decisions indicated by this plan include reducing leakage, and undertaking research and modelling to inform the first decision point in 2022/23 and longer-term decisions. Thames Water, 2019b).

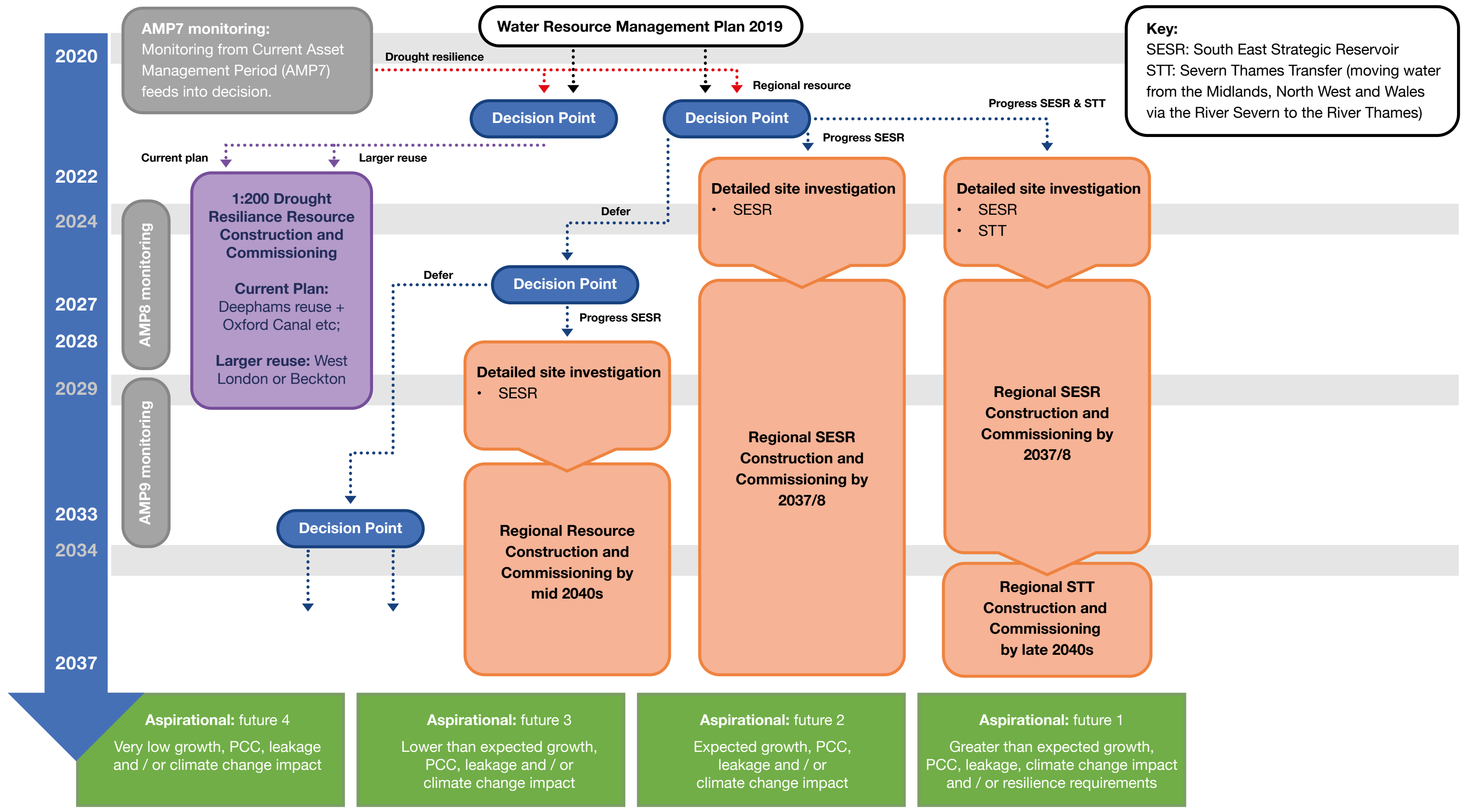


Figure 5: Alternative Options Plan produced by Thames Water for their 2019 Water Resources Management Plan (Thames Water, 2019a). Adaptation pathways have been produced for four different futures using the criteria given in Table 4. Pathway 2, expected: future, is the current preferred option. In 2022/3 a key decision will be made as to whether to stay on this pathway, or move to an alternative. AMP7: the current delivery period between 2020-2024. SESR: Strategic Regional Resource. STT: STT: Severn Thames Transfer (buying water from other water companies in the Midlands, NW England or Wales).

Driver	Aspirational	Optimistic	Expected	Challenging
Deficit change	~150Mld less	~100Mld less	-	~150Mld more
Timing of change	2055	2045	-	2050
Population	ONS16 Low[1]	ONS16 Low[1]	Most likely	CaMKOx
PCC	105lhd by 2065[1]	110lhd by 2065[1]	121lhd by 2045	No reduction[1]
Leakage	Half leakage	Half leakage	Half leakage	Reduced by 1/3[1]
Climate Change	Impact 2080s	Impact 2080s	Impact 2080s	Impact 2050s
Resilience	1:200	1:200	1:200	1:500[1]
Regional need	Delayed 2055[1]	Delayed 2045[1]	100Mild 2037/8	Increased 2050[1]
[1] Single driver which on its own would be sufficient to trigger a different future to that in the Preferred Plan				

Table 4: Single1 and in-combination drivers for the different futures developed by Thames Water as part of their adaptive approach (Thames Water, 2019a). A change in a single driver (e.g. population) will not force a pathway change on its own. PCC: Per Capita Consumption; ONS: Office National Statistics; PCC: lhd: litres/head/day; Mld: million litres of water. CaMKOx: Cambridge, Milton Keynes and Oxford growth corridor

2.4 London: Water resourcing investment decision tree for London, 2020s to 2080s.

Darch et al. (2011) also used adaptation pathways to consider the impact of climate change on water resources in London. Unlike Thames Water (Thames Water, 2019a; Section 2.3), that used time as an axis for the adaptation, Darch et al. used water supply deficit as the axis (Figure 6), and constructed adaptation pathways to address the deficit (where deficit is demand deducted from supply). Projected deficits were determined from different emissions scenarios for 2020, 2050 and 2080s from UKCP09 (Murphy et al., 2099) using existing best practice for extrapolating the data. The adaptation options were sequenced in order of priority, and reducing leakage and compulsory metering form the basis of each adaptation pathway. Once the deficit approaches 300 ml/day, a key decision on strategic investment in the infrastructure is required to meet the larger deficit.

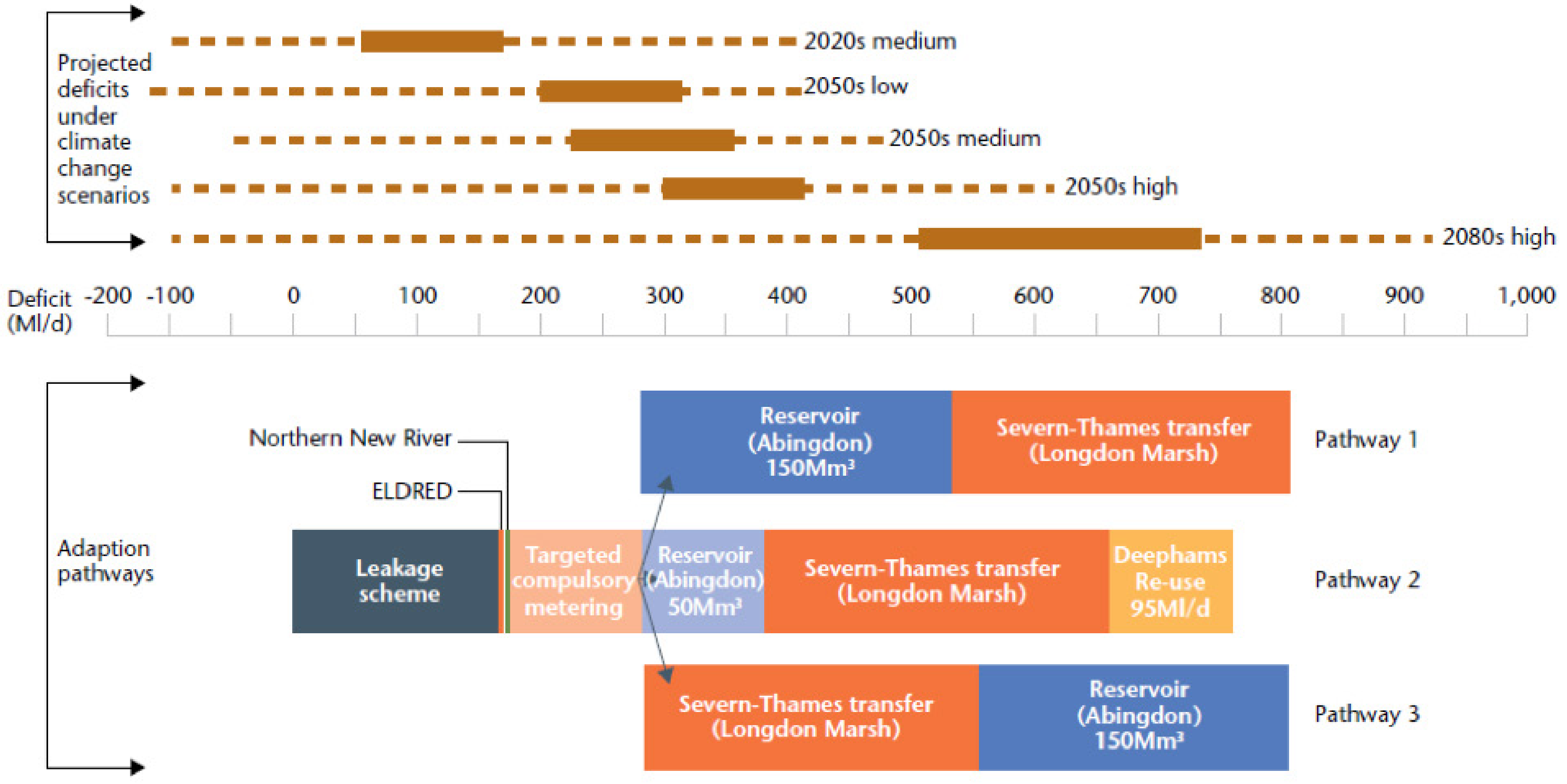


Figure 6: Adaptation pathways for water resource management in London. From Darch et al. (2011).

3. Stakeholder feedback of using an adaptation pathways approach

3.1 The evidence base for evaluating adaptation pathways

Adaptation pathways are widely advocated by academic and practitioner communities as an approach for climate change adaptation that deals with the inherent environmental and socio-economic uncertainties of climate change (e.g. Moss and Martin, 2012; Wise et al., 2014; Maru and Smith, 2014; Barnett et al., 2014; GLA, 2015; Lin et al., 2017; Jacobs et al., 2019;). However, the evidence-base to evaluate the benefits and effectiveness of the adaptation pathways approach for infrastructure operators and policy is limited by three interlinked factors:

1. Although adaptation pathways are applied in range of theoretical contexts, including; coastal flood management (Barnett et al., 2014), urban flood management (Ke et al., 2016), urban drainage (Babovic and Mijic, 2015), urban heat-risk (Kingsborough et al., 2017), and water resource management (Darch et al., 2011; Kingsborough et al., 2016), these adaptation pathways have not translated into practice. Consequently, the evidence base for evaluating the effectiveness of adaptation pathways is limited a handful of exemplars where the pathways approach has been operationalised, such as the Thames Estuary TE2100 project (Ranger et al., 2013; Section 2) and the Dutch Delta Programme (Hasnoot et al., 2013; Bloemen et al., 2018).
2. For those cases where the adaptation pathways approach has been operationalised (i.e. Thames Estuary TE2100 project and Dutch Delta Programme) there are limited reviews of their operational suitability. Those studies of adaptation pathways in practice (Lin et al., 2017; Bloemen et al., 2018) do provide some useful lessons and insights into the benefits and challenges of this approach for infrastructure operators (Section 3.2 and Section 3.3).
3. Many of the theoretical and operationalised examples of adaptation pathways have been developed for one hazard, sea level rise, and focus on a geographic region (Rosenzweig et al., 2011; Ranger et al., 2013; Hasnoot et al., 2013; Barnett et al., 2014; Wall et al., 2015; Lawrence and Hasnoot, 2017; Aerts et al., 2018). Whilst this localised approach is a key principle of adaptation pathways (Section 1.3), there is no theory or practical examples for an adaptation pathway approach for infrastructure operators such as Network Rail, who own multiple asset types (track, signalling, digital), which are impacted differently by a range of climatic impacts (e.g. heat, heavy rainfall, high winds, sea-level rise), over a varied geographic area.

3.2 Benefits of adaptation pathways

The benefits of adaptation pathways for operational practice have been explicitly considered using examples from Australia (Coastal Adaptation Pathways programme), Netherlands (Dutch Delta Programme) and UK (TE2100), and occasionally within individual projects. The key benefits of using adaptation pathways are:

- The process was helpful and could be implemented into existing planning systems (Lin et al., 2015).
- The approach was useful to frame and visualise decisions and keep the decision making-process moving forward (Lin et al., 2015; Bloemen et al., 2018).
- The pathways approach resonated with existing decision-making criteria such as cost effectiveness and 'no/low regrets' adaptation (Lin et al., 2015).
- The approach allows for long-term objectives to be incorporated in short-term decisions (Bloemen et al 2018).
- The process provided increased awareness of uncertainties, and motivated decision-makers to incorporate uncertainty in their decisions and plans (Bloemen et al 2018).
- The pathways enable different measures to be positioned and sequenced in time, such as immediate versus future implementation (Siebentritt et al., 2014; Bloemen et al., 2018).
- The process enabled stakeholder buy in to facilitate implementation and allow for a broader generation of adaptation options (Barnett et al., 2014; Bloemen et al., 2018).

3.3 Challenges of using adaptation pathways

Several challenges of the adaptation pathways approach have been outlined in the academic and practitioner evidence base outlined in Section 3.1. These are:

- Adaptation can focus on (more achievable) incremental actions, and proximate causes, with fewer systemic or transformative actions (Wise et al., 2014; Bloemen et al., 2018).
- There can be a lack of clarity regarding who is financially and legally responsible for decisions and associated impacts, costs and risk mitigation (Lin et al., 2017).
- It can be difficult to determine the tipping points (or thresholds, triggers), especially for those hazards with large natural variability, such as storms, droughts, and heat waves (Bloemen et al., 2018).
- How to encourage broader societal commitment in situations of low predictability; for example, a hazard, such as limited freshwater supply might happen at some point in the future, but why change farming/extraction practices now (Bloemen et al., 2018).
- If there is limited stakeholder engagement then the range of adaptation pathways may be too narrow, preventing the full potential of the pathways approach (Lin et al., 2017).
- Bloemen et al. (2018) also noted that cost benefit analysis constraints can prevent investment, and that decisions may be political. These challenges are not unique to an adaptation pathways approach. Additionally, the vulnerability of assets and infrastructure can change due to aging, damage, or poor maintenance, and the social or government acceptance of disruption can change, thereby leaving quantitative cost benefit or multi-criteria analyses outdated.

5. Applying adaptation pathways in the UK

5.1 General approaches to applying adaptation pathways

The adaptation pathways approach provides a systematic framework for any organisation to design flexible adaptation options that incorporate the uncertainties associated with climate change, or other socio-economic unknowns. Adaptation pathways can be developed in for a range of business functions including asset management (e.g TE2100, Section 2.1), emergency response (e.g New York, Rosenzweig and Solecki, 2014), supply chain management or strategic investment (e.g. Thames Water, Section 2.3). The specifics of the pathways approach will depend on the organisational structure, and their adaptation requirements.

Figure 7 shows a generic framework for developing adaptation pathways that combines approaches developed by Quinn et al. (2018) on the Rail Adapt project, and Trioss2 from their substantive experience of working with organisations including the Environment Agency (TE2100; Section 2.1; Reeder & Ranger 2011) and local authorities (e.g. Somerset, Trioss et al., 2019). The framework is designed to be used by any infrastructure operator, local authority, environmental manager and more, regardless of their level of preparedness, to start or facilitate the process of climate adaptation. The right side of the framework draws on the Rail Adapt project that worked with global transport stakeholders from more than 50 organisations in 20 countries via a series of international workshops (Quinn et al., 2018). Via a series of steps it defines the adaptation requirements by considering the impact of current and future climate change, in particular focussing on high-end low probability climate scenarios (e.g. Reeder & Ranger 2011). The steps encourage stakeholder engagement, encouraging the inclusion of experience and tacit knowledge, and should align with the exiting management approach, and the specific context and asset portfolio. The left side of the framework draws on the nine steps to develop adaptation pathways used by the TE2100 project (Table 2) and best practice advice provided by Trioss (Table 5). The framework enables iterative review and updating, which is fundamental to the pathways approach (Section 1.3). Regular reassessment ensures the process is iterative, and that new information can be regularly updated to ensure the pathways remain relevant as socio-economic circumstances and climatic hazards change.

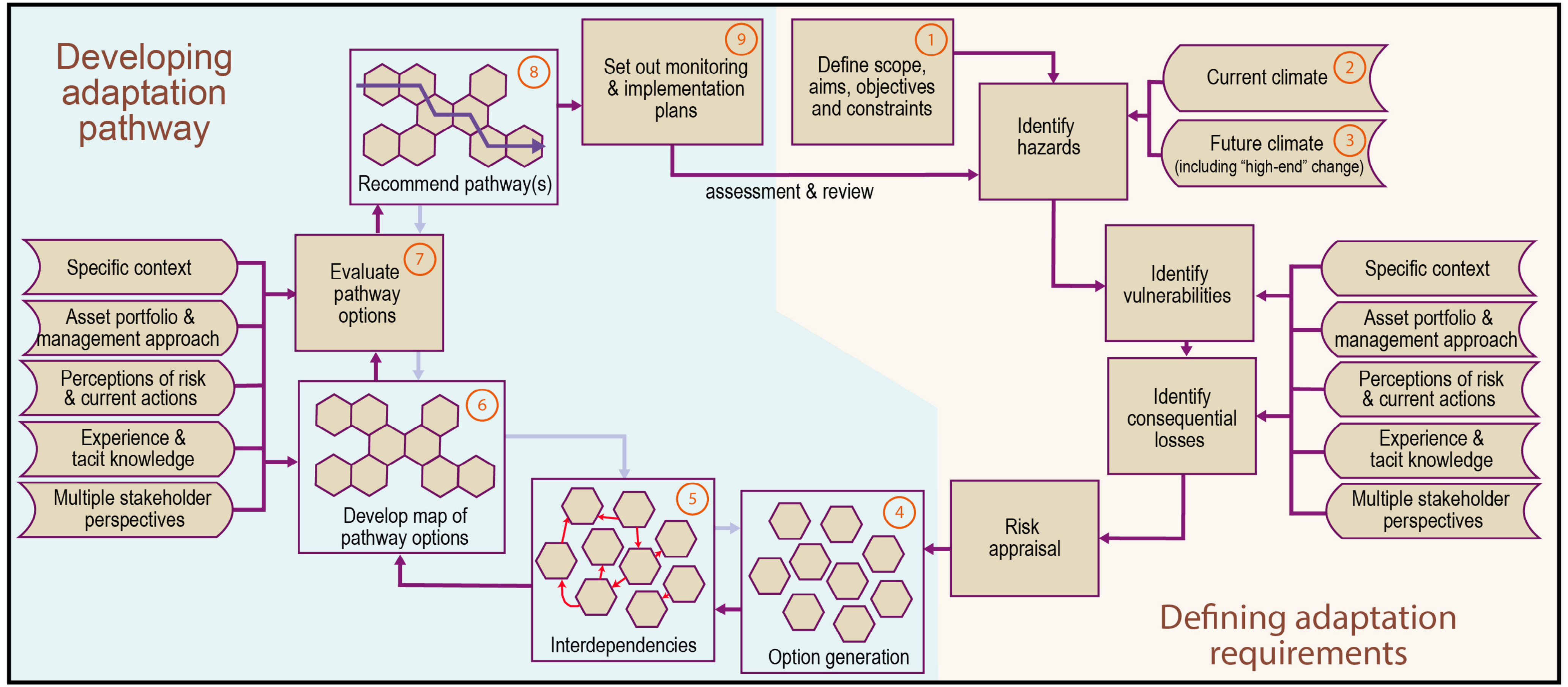


Figure 7: Generic framework for developing adaptation pathways that combines approaches developed by Quinn et al. (2018) on the Rail Adapt project, and Trioss (e.g. Reeder & Ranger 2011). Orange encircled numbers link to Table 5.

5.2 Industry standards for climate adaptation and adaptation pathways

Most infrastructure operators and owners have well-defined and established procedures for daily operations and long-term strategic management. These may follow the international standards developed by the International Organisation for Standardisation (ISO), including: ISO55000 in asset management, ISO9000 for quality assurance, ISO26000 covering social responsibility and environmental impacts, ISO31000 in risk management for safety and financial planning, or ISO22316 for organisational resilience. Additionally, ISO14000 provides a family of standards for environmental management that support the design of environmentally friendly products and services. Considering climate change within these existing operations and procedures will ensure that adaptation becomes part of business as usual (Quinn et al., 2018).

Moreover, in 2019 ISO released the first international standards for managing the impact of climate change. ISO 14090, Adaptation to climate change – Principles, requirements and guidelines, and ISO 14091, Adaptation to climate change – Vulnerability, impacts and risk assessment4. These standards provide guidelines for organisations to identify and therefore manage the risks and opportunities of climate change (for information on ISOs supporting climate change see: ISO, 2018). It supports policy design and implementation, and links to the United Nations' Sustainable Development Goal on climate action (SDG 13). Within the UK, the British Standards Institution is drafting a standard, BSI 8631 Decision making for climate change – Adaptation pathways5. This will support those wishing to produce adaptation pathways by providing requirements with guidance on good practice. There will be different entry levels to support both those organisations at the outset of constructing adaptation pathways, and those who require guidance to develop thresholds/tipping points, or those who wish to test the robustness of a pre-existing pathways approach.

Lastly, the Energy Technologies Institute (ETI) have produced as series of technical volumes and five case studies that characterise a series of natural hazards, including high temperature, extreme wind, extreme precipitation, lightning, river flooding and coastal flooding (ETI, 2018).

Table 5: Further details and the types of questions to consider in order to apply the steps to develop climate change adaptation pathways (Figure 7). Adapted from material provided by Trioss. © Trioss.

1.Define: scope, aims, objectives and constraints.	• What are you trying to achieve? • Over what time scale? • With what level of analysis? • With what level of certainty?
2. Understand the risk and opportunity from the current climate.	• What are the environmental factors affecting the current system? • What are the most critical issues? • What decisions that affect risk and opportunity do you - have control over? - not have control over?
3. Understand risk / opportunity from a range of future climate scenarios, including the high end low probability climate scenarios such as Met Office H++.	• What scale of climate scenario will make sure all change requirements are covered? • What things "fail" when, on the pathway towards that scenario? • What are the localised and systemic implications?
4. Consider adaptation options for different levels of risk and opportunity and their thresholds.	When a threshold is reached, what needs to change to still achieve your objectives? • physical adaptations? • behavioural change? • land-use planning change? • economic incentives? • regulatory change?

Table 5: Further details and the types of questions to consider in order to apply the steps to develop climate change adaptation pathways (Figure 7). Adapted from material provided by Trioss. © Trioss.

5. Consider interdependencies with other drivers and modify options.	• What are the other drivers of change that affect the delivery of your objective? • Socio-economic e.g. population, • economic or political change • the vulnerability of services e.g. power, communications • Any particular vulnerability? E.g. climate change?
6. Assemble a route map (pathway) options in response to risks / opportunities that will tackle thresholds.	• What are the most effective combination of responses to each threshold failure? • Looking ahead, how do you most effectively enable the responses to meeting future thresholds?
7. Evaluate pathway options.	What methodology and effort level best suites your needs? Things to consider may include:- • participation, • modelling, • cost benefit analysis, • multi-criteria analysis, • co-creation with stakeholders
8. Recommend preferred pathways	• Who are the decision makers? • How do you "take them with you"? • How do you "sell" the way forward
9. Set out implementation and monitoring plans and learning framework	• How much effort are you going to put into monitoring effectiveness? • How do you retain interest over time and change plans as understanding and answers to the previous questions change? • What is the most effective implementing and monitoring approach given these answers?

5.3 Concluding insights and recommendations for applying adaptation pathways in UK

This briefing note has reviewed global best practice in designing and implementation adaptation pathways for infrastructure operators and policymakers, focusing on their relevance for the UK. Within the UK, the Environment Agency are international advocates with key expertise of applying adaptation pathways. The Environment Agency they were part of the pioneering TE2100 project (Reeder and Ranger, 2011), they have proposed adaptive pathways to water utilities as part of their Water Resource Management Plans (Thames Water, 2019c; United Utilities, 2019) and they have co-delivered training sessions on adaptation pathways at international conferences such as the European Climate Change Adaptation Conference in Lisbon, Portugal, 2019 (Eden et al., 2019). ClimateXChange6, who provide research, advice and analysis service to Scottish Government were early advocates of this approach (Moss and Martin, 2012), and a Flexible Adaptation Pathways approach has been considered for native Scottish Woodland (Moffat et al., 2014). Climate Ready Clyde7, a cross-sector initiative to create an adaptation plan for the Glasgow City Region, value the pathways approach, but found themselves overwhelmed by a need for detail that they didn't have, and felt that thresholds may change as appetite for risk and evidence change; they look forward to standardised guidance from the BSI (Trioss, pers. comm., Apr 2020). The Greater London Authority Environment Committee endorse the use of an adaptation pathways, but did not apply the approach in the 2015 Mayor's Climate Change Adaptation Strategy, as there was considered to be insufficient details on climate risks (GLA, 2015). Consultancies such as Atkins (e.g. Darch et al., 2011), Trioss (e.g. Trioss, 2019; BSI 8631, Eden et al., 2019), and JDCL (e.g. Quinn et al., 2017; 2018; ISO14090) have supported adaptation pathways and developed guidance for several organisations.

The publication of the 2019 ISO14090 and 14091 standards for climate adaptation, and the forthcoming BSI with specific guidance to design and implement adaptation pathways, combined with the pathways created by the water utilities (Thames Water, 2019a; United Utilities, 2019), and local authorities (e.g. Somerset, Trioss, 2019;) suggests that this internationally accepted best-practice approach is becoming increasingly mainstreamed by infrastructure operators in the UK. In conclusion, there are several insights and recommendations from the practitioner and academic evidence base to create successful adaptation pathways.

From Trioss (N. Pyatt & T. Reeder, pers. comm., Apr 2020, quoted verbatim): avoid the need to be perfect getting in the way of the good. Whilst there is a temptation to be sucked into the need to be "right" and therefore the need for evidence, which is almost inevitably not available within the budget, there is huge value in, where necessary, applying "expert judgement" where evidence may be weak, and so developing the best picture available at the moment. Those that take this approach find the results hugely useful. It brings stakeholders together to explore interdependencies and develops the concepts of thresholds which:

- Make clear not everything has to be done now.
- Make clear to people new to adaptation how to consider a future that holds different risks which need to be considered in today's decisions.
- What opportunities there are to act now.
- How future adaptation requirements can be implemented more easily if there is a slightly different approach taken to today's decisions.
- Using the 80:20 principle, a lot that is clear can be quickly identified.
- The areas requiring much more details can be prioritised.
- The plan provides a framework for reflection and revision as understanding develops i.e. it is used as a living document to guide reflection as well as action.

Relevant highlights from feedback from infrastructure stakeholders who used the climate adaptation framework developed by Quinn et al. (2018) that supports an adaptive approach include:

- The framework was useful to move the climate change adaptation agenda forward within their organisation or country to initiate conversations and raise awareness.
- In the first instance the framework should be taken to senior management, or government officials to gain high-level support, particularly where climate adaptation is a low priority.
- Audience appropriate language is important. Terms such as "risk and asset management", "sustainability" and "extreme weather", which are already part of infrastructure planning and policy can encourage broader stakeholder buy in and help them see how to embed adaptation as part of business as usual. (In the UK where there is strong and mandatory requirements for climate change adaptation this is likely to be less of an issue, but it may be relevant for those organisations with international remit).

From Bloemen et al. (2018) who considered the application of adaptation pathways in Netherlands (Dutch Delta Programme) and the UK (TE2100 project):

- Encourage "free thinking space" to consider actions that may not be acceptable either politically or financially in the short term.
- Early drafts of the pathway diagrams help communicate concepts and engage stakeholders.
- Review and update the pathways
- Co-ordinate processes at a high level to ensure consistency.
- Ensure local knowledge and tacit information from key stakeholder is included in the development of the pathways.

6. References

Aerts, J.C., Barnard, P.L., Botzen, W., Grifman, P., Hart, J.F., De Moel, H., Mann, A.N., de Ruig, L.T. and Sadrpour, N., 2018. Pathways to resilience: adapting to sea level rise in Los Angeles. Annals of the New York Academy of Sciences, 1427(1), pp.1-90.

Babovic, F. and Mijic, A., 2019. The development of adaptation pathways for the long-term planning of urban drainage systems. Journal of Flood Risk Management, 12(S2), p.e12538.

Barnett, J., Graham, S., Mortreux, C., Fincher, R., Waters, E. and Hurlimann, A., 2014. A local coastal adaptation pathway. Nature Climate Change, 4(12), pp.1103-1108.

Brown, R., Curley, J. and Smith, B., 2014. Transport resilience review: a review of the resilience of the transport network to extreme weather events. Department for Transport: London (UK).

Bloemen, P., Reeder, T., Zevenbergen, C., Rijke, J. and Kingsborough, A., 2018. Lessons learned from applying adaptation pathways in flood risk management and challenges for the further development of this approach. Mitigation and adaptation strategies for global change, 23(7), pp.1083-1108.

Dawson, D., Shaw, J. and Gehrels, W.R., 2016. Sea-level rise impacts on transport infrastructure: The notorious case of the coastal railway line at Dawlish, England. Journal of Transport Geography, 51, pp.97-109.

Darch, G., Arkell, B. and Tradewell, J. 2011. Water resource planning under climate uncertainty in London. Atkins Report (Reference 5103993/73/DG/035) for the Adaptation Sub-Committee and Thames Water. Atkins, Epsom. http://archive.theccc.org.uk/aws2/ASC%202nd%20Report/ASC-Water-CaseStudy_Final.pdf Accessed 05/04/2020.

EA (2012) TE2100 Plan: Managing flood risk through London and the Thames estuary. Environment Agency, UK. November 2012. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/322061/LIT7540_43858f.pdf Accessed 08/04/2020.

EA (2010) Flood and coastal erosion risk management appraisal guidance (FCERMAG). Environment Agency, UK.

Eden, A., Francis, K., Reeder, T., Hassnoot., M. 2019. Adaptation pathways – from trailblazing to trail guide: Learning from practical implementation of adaptation pathways approach and shaping a guide/standard. In Data, methods and approaches in Climate Change Adaptation and Disaster Risk Reduction, at 3rd European Climate Change Adaptation Conference. Lisbon, Portugal, 28th-30th May, 2019.

GLA, 2015. Come rain or shine London's adaptation to the risks of severe weather. Greater London Authority. Environment Committee. March 2015. https://www.london.gov.uk/sites/default/files/Come%20rain%20or%20shine%20report.pdf. Accessed 05/04/2020.

ETI. 2018. Enabling Resilient UK Energy Infrastructure: Natural Hazard Characterisation Technical Volumes and Case Studies, Volume 1 – Introduction to the Technical Volumes and Case Studies. IMechE, IChemE. Energy Technologies Institute LLP. 24th August 2018. https://www.imeche.org/policy-and-press/from-our-perspective/energy-theme/enabling-resilient-uk-energy-infrastructure Accessed 16/05/2020.

Ferranti, E., Chapman, L. and Whyatt, D., 2017. A Perfect Storm? The collapse of Lancaster's critical infrastructure networks following intense rainfall on 4/5 December 2015. Weather, 72(1), pp.3-7.

Fung F, Palmer M, Howard T, Lowe J, Maisey P and Mitchell JFB (2018). UKCP18 Factsheet: Sea Level Rise and Storm Surge, Met Office Hadley Centre, Exeter. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-fact-sheet-sea-level-rise-and-storm-surge.pdf Accessed 08/04/2020.

Haasnoot, M., Kwakkel, J.H., Walker, W.E. and ter Maat, J., 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global environmental change, 23(2), pp.485-498.

Haasnoot, M., Warren, A. and Kwakkel, J.H., 2019. Dynamic Adaptive Policy Pathways (DAPP). In Decision Making under Deep Uncertainty (pp. 71-92). Springer, Cham.

IPCC, 2013: Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

ISO 2018. ISO and Climate Change. Great things happen when the world agrees. International Organization for Standardization. Geneva, Switzerland. 2018. https://www.iso.org/files/live/sites/isoorg//files/store/en/PUB100067.pdf Accessed 14/04/2020.

Jacobs, B., Boronyak, L. and Mitchell, P., 2019. Application of Risk-Based, Adaptive Pathways to Climate Adaptation Planning for Public Conservation Areas in NSW, Australia. Climate, 7(4), p.58.

Ke, Q., Haasnoot, M. and Hoogvliet, M., 2016. Exploring adaptation pathways in terms of flood risk management at a city scale–a case study for Shanghai city. In E3S Web of Conferences (Vol. 7, p. 21002). EDP Sciences.

Kingsborough, A., Borgomeo, E. and Hall, J.W., 2016. Adaptation pathways in practice: mapping options and trade-offs for London's water resources. Sustainable cities and society, 27, pp.386-397.

Kingsborough, A., Jenkins, K. and Hall, J.W., 2017. Development and appraisal of long-term adaptation pathways for managing heat-risk in London. Climate Risk Management, 16, pp.73-92.

Kwadijk, J.C., Haasnoot, M., Mulder, J.P., Hoogvliet, M.M., Jeuken, A.B., van der Krogt, R.A., van Oostrom, N.G., Schelfhout, H.A., van Velzen, E.H., van Waveren, H. and de Wit, M.J., 2010. Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. Wiley interdisciplinary reviews: climate change, 1(5), pp.729-740.s for London's water resources. Sustainable cities and society, 27, pp.386-397.

Lin, B.B., Capon, T., Langston, A., Taylor, B., Wise, R., Williams, R. and Lazarow, N., 2017. Adaptation pathways in coastal case studies: lessons learned and future directions. Coastal Management, 45(5), pp.384-405.

Lawrence, J. and Haasnoot, M., 2017. What it took to catalyse uptake of dynamic adaptive pathways planning to address climate change uncertainty. Environmental Science & Policy, 68, pp.47-57.

Maru, Y.T. and Smith, M.S., 2014. GEC special edition–Reframing adaptation pathways. Global Environmental Change, 100(28), pp.322-324.

Moffat, A.J., Ellis, C., Moss, A., Nicoll, B., Martin, S. and Beauchamp, K., 2014. Scottish Native Woodland Adaptation–the potential use of a Flexible Adaptation Pathways Framework. A ClimateXChange report for Scottish Government. https://www.climatexchange.org.uk/media/1563/scottish_native_woodland_adaptation.pdf Accessed 14/04/2020.

Moss. A & Martin, S (2012) Flexible Adaptation Pathways. A ClimateXChange report for Scottish Government. https://www.climatexchange.org.uk/media/1595/flexible_adaptation_pathways.pdf Accessed 05/04/2020.

Murphy, J. M., Sexton, D. M. H., Jenkins, G. J., Booth, B. B. B., Brown, C. C., Clark, R. T., Collins, M., Harris, G. R., Kendon, E. J., Betts, R. A., Brown, S. J., Humphrey, K. A., McCarthy, M. P., McDonald, R. E., Stephens, A., Wallace, C., Warren, R., Wilby, R., Wood, R. A. 2009. UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, Exeter.

Nikkels, M.J., Kumar, S. and Meinke, H., 2019. Adaptive irrigation infrastructure–linking insights from human-water interactions and adaptive pathways. Current Opinion in Environmental Sustainability, 40, pp.37-42.

Nguyen, A., Dix, B., Goodfried, W., LaClair, J., Lowe, L., Yokoi, S. and Fahey, R., 2011. Adapting to rising tides–Transportation vulnerability and risk assessment pilot project. Technical Rep.

Quinn, A.D.; Jack, A.; Hodgkinson, S.; Ferranti, E.J.S.; Beckford, J.; Dora, J. 2017 Rail Adapt: Adapting the Railway for the Future; A Report for the International Union of Railways (UIC); UIC: Paris, France, 2017. https://uic.org/IMG/pdf/railadapt_final_report.pdf Accessed 13/04/2020.

Quinn, A.D., Ferranti, E.J., Hodgkinson, S.P., Jack, A.C., Beckford, J. and Dora, J.M., 2018. Adaptation Becoming Business as Usual: A Framework for Climate-Change-Ready Transport Infrastructure. Infrastructures, 3(2), p.10.

Ranger, N., Reeder, T. and Lowe, J., 2013. Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. EURO Journal on Decision Processes, 1(3-4), pp.233-262.

Reeder, T. and Ranger, N., 2011. How do you adapt in an uncertain world?: lessons from the Thames Estuary 2100 project. World Resources Report Washington DC. Available online at http://www.worldresourcesreport.org

Rosenzweig, C., Solecki, W.D., Blake, R., Bowman, M., Faris, C., Gornitz, V., Horton, R., Jacob, K., LeBlanc, A., Leichenko, R. and Linkin, M., 2011. Developing coastal adaptation to climate change in the New York City infrastructure-shed: process, approach, tools, and strategies. Climatic change, 106(1), pp.93-127.

Rosenzweig, C. and Solecki, W., 2014., 2014. Hurricane Sandy and adaptation pathways in New York: Lessons from a first-responder city. Global Environmental Change, 28, pp.395-408.

Siebentritt, M., Halsey, N. and Stafford-Smith, M. (2014). Regional Climate Change Adaptation Plan for the Eyre Peninsula. Prepared for the Eyre Peninsula Integrated Climate Change Agreement Committee.

Taleb, N. N. (2007). The black swan, Random House, New York.

Tanaka, A., Takahashi, K., Masutomi, Y., Hanasaki, N., Hijioka, Y., Shiogama, H. and Yamanaka, Y., 2015. Adaptation pathways of global wheat production: Importance of strategic adaptation to climate change. Scientific reports, 5, p.14312.

Wade, S., Sanderson, M., Golding, N., Lowe, J., Betts, R., Reynard, N., Kay, A., Stewart, L., Prudhomme, C., Shaffrey, L. and Lloyd-Hughes, B., 2015. Developing H++ climate change scenarios for heat waves, droughts, floods, windstorms and cold snaps. A report by the Met Office for the Adaptation Sub-Committee. UK: Exeter. October 2015. https://www.theccc.org.uk/wp-content/uploads/2015/10/Met-Office-for-the-ASC-Developing-H-climate-change-scenarios-for-heatwaves-droughts-floods-windstorms-and-cold-snaps3.pdf Accessed 08/04/2020.

Thames Water 2019a. Section 11 – Preferred Programme, adaptive pathway and further work. Water Resources Management Plan 2019. Thames Water. London, UK. April 2019. https://corporate.thameswater.co.uk/-/media/Site-Content/Your-water-future-2019/updates/Section-11--Preferred-Programme-adaptive-pathway-and-further-work.pdf Accessed 09/04/2020.

Thames Water 2019b. Section 10 – Programme appraisal and scenario testing. Water Resources Management Plan 2019. Thames Water. London, UK. April 2019. https://corporate.thameswater.co.uk/-/media/Site-Content/Your-water-future-2019/updates/Section-10--Programme-Appraisal-and-Scenario-Testing.pdf Accessed 09/04/2020.

Thames Water 2019c. Shape your water future. Feedback from the further consultation on our revised draft Water Resources Management Plan 2019 and an overview of our plan. Thames Water. London, UK. April 2019. https://corporate.thameswater.co.uk/-/media/Site-Content/Your-water-future-2019/Overview--April-2019.pdf Accessed 14/04/2020.

Trioss 2019. CO-ADAPT Workshop 2 Report: Reviewing Somerset Flood Resilience Plans With Technical Specialists. Part of the Co-Adapt initiative: Planning a Long Term and Thriving Somerset in a Changing Climate. Trioss, Devon UK.

UKCP 2019. UK Climate Projections: Headline Findings. Met Office, Exeter UK. September 2019. Version 2. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp-headline-findings-v2.pdf. Accessed 10/04/2020.

United Utilities 2019. United Utilities Final Water Resources Management Plan 2019. United Utilities, Warrington, UK. https://www.unitedutilities.com/globalassets/z_corporate-site/about-us-pdfs/wrmp-2019---2045/final-water-resources-management-plan-2019.pdf Accessed 14/04/2020.

Wall, T.A., Walker, W.E., Marchau, V.A. and Bertolini, L., 2015. Dynamic adaptive approach to transportation-infrastructure planning for climate change: San-Francisco-Bay-Area case study. Journal of Infrastructure Systems, 21(4), p.05015004.

Walker, W.E., Rahman, S.A. and Cave, J., 2001. Adaptive policies, policy analysis, and policy-making. European Journal of Operational Research, 128(2), pp.282-289.

Wise, R.M., Fazey, I., Smith, M.S., Park, S.E., Eakin, H.C., Van Garderen, E.A. and Campbell, B., 2014. Reconceptualising adaptation to climate change as part of pathways of change and response. Global Environmental Change, 28, pp.325-336.

Wise R., Butler, J., Capon, T., Colloff, M., Dunlop, M., Gorddard, R., Maru, R., Meharg, S., O'Connell, D., Ryan, P., Stafford Smith, M., Stone Jovicich, S., and Williams R., 2016. What are adaptation pathways? ASSAR Webinar - "Adaptation pathways: From concept to Practice". http://www.assar.uct.ac.za/sites/default/files/image_tool/images/138/webinar/What%20are%20adapation%20pathways%20-%20Russ%20Wise%20-%2014%20Oct%202016.pdf Accessed 04/04/2020.

Web references:

1. Deltares: https://www.deltares.nl/en/adaptive-pathways/. Accessed 06/04/2020.

2. Trioss: https://www.trioss.global/ Accessed 11/04/2020.

3. International Organization for Standardization: ISO14090 Adaptation to climate change – Principles, requirements and guidelines https://www.iso.org/obp/ui/#iso:std:iso:14090:ed-1:v1:en Accessed 14/04/2020.

4. International Organization for Standardization: ISO14091 Adaptation to climate change – Guidelines on vulnerability, impacts and risk assessment https://www.iso.org/obp/ui/#iso:std:iso:14091:dis:ed-1:v1:en Accessed 14/04/2020.

5. British Standards Institution: Standards Development BS XXXX Decision making for climate change – Adaptation pathways https://standardsdevelopment.bsigroup.com/projects/9018-01780#/section

6. ClimateXChange: https://www.climatexchange.org.uk/ Accessed 14/04/2020.

7. Climate Ready Clyde: http://climatereadyclyde.org.uk/ Accessed 14/04/2020.