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Taking a managed adaptive approach to flood risk management planning in Scotland

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Executive summary

This report assesses the use of managed adaptive flood risk planning in Scotland in the context of increasing and uncertain risks relating to climate change. It considers whether Scottish planning follows international best practice in this emerging field and, where there are shortcomings, seeks to identify how these stem from legislation, regulatory guidance or practitioner capacity. Drawing on Scottish case study evidence, it presents recommendations for how guidance can be changed to facilitate more adaptive approaches in cases where this can be valuable. Vivid Economics and HKV were commissioned by ClimateXChange to carry out this study. This final report presents the findings of the work.

Value of adaptive approaches

Managed adaptive approaches to planning can outperform traditional methods in the context of climate change. Managed adaptive flood risk planning, unlike traditional 'predict then adapt' approaches, anticipates the fact that as learning about the climate takes place, future Flood Risk Management (FRM) planners will have more detailed information on flood risks than current planners. It therefore places a positive value on affording future FRM planners *flexibility* to adapt appropriately to the superior information on risks that they will have at their disposal.

The economic and academic literature presents methodologies to develop and appraise flexible, adaptive plans. Adaptive plans set out sequences of multiple actions and define 'trigger points' where FRM planners flexibly switch between courses of action on the basis of new information. The 'Dynamic Adaptive Policy Pathway' (DAPP) approach defines potential 'pathways' of actions that can be considered in an economic appraisal. Real options analysis then values the benefit-cost ratio of alternative pathways, accounting fully for the prospective benefits of flexibility, the costs of flexibility (for example, the cost of building a sea wall with a higher base than is needed to meet the objective for current protection), and the probability that FRM planners will wish to exercise flexibility in the future.

International experience shows how these theoretical approaches can be implemented in practical settings. A review of practitioner literature, including international case studies, highlights how practical barriers in implementing adaptive approaches that arise across the planning process can be overcome. In particular, evidence from the Delta programme in the Netherlands highlights the formal adoption of 'flexibility' as a performance criterion, the identification of tipping points – and associated 'trigger points' that account for implementation lead times – and the use of real options analysis in investment appraisal. Planners in New Zealand have successfully engaged the public to engender more widespread acceptance of adaptive approaches, while guidance in England and Wales uses 'adaptability' in multi-criteria analysis to shortlist schemes.

Use of adaptive approaches in Scotland

In Scotland, high-level guidance strongly endorses managed adaptive planning. The guidance states that flood risk management planning should be forward looking, acknowledge that future climate change risk is uncertain, promote managed adaptive planning as a means for dealing with this uncertainty, and endorse the use of real options analysis for appraising climate-sensitive investments. SEPA and the responsible authorities (RAs) are directed to avoid making decisions that will make it more difficult to manage the effects of climate change in the future, in particular by not taking actions now which limit further adaptation in the future(Scottish Government, 2019).

Schemes carried forward within the current planning cycle do not include adaptive plans. Of 42 flood risk management schemes approved for the current planning cycle, 25 schemes are designed to provide a fixed standard of protection, of which 11 include an allowance for the future. None of the schemes incorporate adaptive plans or make reference to multiple climate change scenarios.

Scottish case studies examined by this study nonetheless show that adaptive planning is both feasible and valuable, across a variety of relevant contexts. This report examines four case studies, in the Clyde River corridor, Stonehaven, Eddleston and Newburgh, each where aspects of adaptive planning are under development. Collectively, these case studies span urban and rural settings where coastal, fluvial and surface water flooding risks are key concerns. The review of the case studies exposes:

- **Value of adaptive planning:** in the Clyde, Stonehaven, and Newburgh**,** interventions *sequenced* as risks increase offer greater value for money than traditional once-and-for-all interventions. Economic modelling by this project shows that more adaptive planning, where future interventions are *contingent* on triggers, could offer better value for money still. The value of adaptive approaches is likely to be greatest in settings where significant economic development is expected and potential interventions include large scale natural flood management interventions.

- **Feasibility of adaptive planning:** pragmatic approaches to modelling can generate and appraise adaptive plans, even in rural settings where resources for flood studies are likely to be limited. Where local authorities have required dynamic plans in the terms of reference for flood studies, consultants have proven capable of delivering on this.

Barriers to adaptive approaches

This report identifies five critical barriers to the use of managed adaptive planning in Scotland. These barriers have been identified by comparing current Scottish practice to international best practice, through interviews with stakeholders involved in all stages of decision making, through the examination of case studies, and through a workshop at Scotland's Flood Risk Management Conference 2019. They are:

- **The lack of an adaptive mindset among all stakeholders, including practitioners and the general public**. While high-level official guidance promotes adaptive approaches, there is a widespread lack of comprehension of why this is important and what it entails. This is reflected in there having been no inclusion of flexible decision making in the 2015 Flood Risk Management Strategies. In addition, the Scottish public has not been seriously engaged on the benefits of adaptive planning; as a consequence, there is a perception among FRM planners that communities are less likely to be accepting of adaptive plans.

- **The lack of a standardised methodology to generate adaptive plans.** There is an absence of practical guidance on how to develop adaptive plans, including the identification of tipping and trigger points and the development of adaptive pathways. This means that there is a formidable methodological hurdle faced in developing dynamic plans, which FRM planners seldom have the capacity or resources to overcome. By producing a standardised methodology, the costs and risks associated with generating adaptive plans could be significantly reduced.

- **The lack of a standardised methodology for economic appraisal of adaptive plans.** Even if adaptive plans were developed, there remains a hurdle in assessing the value of these plans and comparing these to traditional structural actions. A standardised methodology would include guidance on the specification of probabilities for scenarios and recommendations on the use of software or calculation methodologies.

- **Funding mechanisms can disincentivise managed adaptive planning and promote large scale interventions.** This stems from two features of the funding regime. First, in any FRM planning cycle, Local Authorities compete against each other for a fixed budget of central Government funds, without clarity around the level of funding in future funding cycles. Second, the large majority of the capital grant from central Government is allocated to large scale schemes, with local authorities reporting limited funding for operations and maintenance/adaptation of existing schemes. Together, this incentivises Local Authorities to promote new capital-intensive inflexible schemes which use central government funding – since such schemes are less 'risky' to deliver than adaptive plans where funding for future adaptation might be unavailable.

- **Planning boundaries.** Although Local Plan Districts follow catchment boundaries, detailed options appraisals are commissioned by Local Authorities, whose boundaries do not align with catchments. This means that catchment-level modelling of risks and mitigation options tends not to be conducted, inhibiting catchment level planning. This is of particular importance where natural flood management schemes are under consideration – as such schemes tend to produce benefits downstream from the intervention sites *and* are often more adaptable than other types of scheme.

Recommendations

To address some of these barriers, this report makes recommendations to extend SEPA guidance on adaptive planning and conduct more research. The recommendations set out more prescriptive guidance on how adaptive planning should be implemented, assisting FRM planners in overcoming methodological hurdles and ensuring a greater degree of consistency between RAs. Recommendations include that:

- Local FRM planners specify within their objectives (i) to manage flood risk at the catchment level, and (ii) to manage uncertain risks, noting that uncertainty on the climate and local exposure/vulnerability is expected to unfold over time. These aspects of the objectives should be made explicit in invitations to tender for flood studies.

- Where an adaptive approach is to be followed, candidate plans are constructed following four steps: (i) plans are built up from a set of schemes, including NFM options, that individually provide a range of standards of protection; (ii) schemes are screened using a multi-criteria approach that accounts for the benefits of flexibility; (iii) trigger points are identified under a set of climate or development scenarios, in which schemes cease to provide an acceptable level of protection; (iv) candidate plans are developed as sequences of contingent interventions, which can be triggered by future assessments of flood risk, designed to provide acceptable levels of protection over the whole planning horizon.

- Plans are appraised using a net present value criterion based on real options analysis, which accounts for the likelihood of different climate or development scenarios.

- Plans are implemented and updated using risk models held by RAs.

Table 1 lists the eight key recommendations this report makes on the conduct of flood risk management planning. In addition, we recommend further research in two critical technical areas in order to elaborate upon this guidance: in assessing the likelihood of climate scenarios, and in estimating damages over time and across scenarios.

Table 1 Recommendations

Number	Recommendation
Setting objectives	
1	If risk is sensitive to uncertain future climate and/or socio-economic scenarios, require this sensitivity to be accounted for in tenders for flood studies. In such cases, recommendations 2-8 below apply.
Developing adaptive plans	
2	Options appraisal studies should assess risks and potential actions in whole catchment areas.
3	In shortlisting interventions, follow a multi-criteria approach in which 'adaptability' is included as a criterion.
4	Identify trigger points, through the following steps: I. Engage with the community to identify an 'acceptable' level of risk, expressed in Average Annual Damages (AAD); II. Assess climate risks under various scenarios to identify tipping points at which AAD exceeds the acceptable level; III. Account for intervention lead times and planning cycles to specify trigger points at which decisions may need to be taken in order to avoid unacceptable levels of risk.
5	Develop candidate plans, in which potential interventions are introduced at trigger points, contingent on scenario realisations. Plans must include 'do nothing' and 'do maximum' options.
Economic appraisal of plans	
6	Select plans based on a Net Present Value (NPV) criterion, where NPV is calculated using probabilities of all scenarios and Average Annual Damages under each scenario.
Implementing plans	
7	Set up necessary monitoring processes in order to verify trigger points.
8	Maintain risk models within RAs so they can be updated at low cost as new information becomes available.

Source: Vivid Economics

Content

1 Introduction

1.1 Context

Scotland's climate is changing. Annual average temperatures in Scotland are 0.7°C higher than a century ago, sea levels have risen by 10cm since the 1920s, and annual average rainfall has increased by 13% since the early 20th century(The Committee on Climate Change, 2016). Globally, it is widely expected that average annual temperatures will rise between 2 and 4°C by the end of the 21st century.

Climate change will increase flood risk in Scotland. The latest UK Climate Projections (UKCP18) project milder, wetter winters in Scotland with more extreme precipitation events and higher sea levels (Scottish Government, 2019b). Average summer precipitation is expected to decrease, but with more intense extremes (Chan et al, 2018). As a consequence of this, estimates of flood risk that are based on observations of the past will generally understate future risks. In Scotland, wetter winters are expected to increase risk in areas currently exposed to flood as well as potentially putting new areas at risk (Scottish Government, 2011), and higher sea levels will increase flood risk and likelihood of erosion.

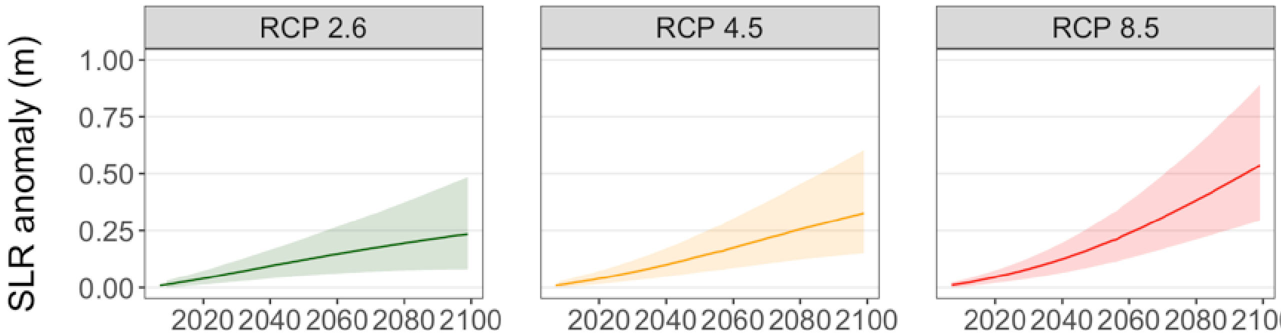
The magnitude of the change is uncertain due to a cascade of uncertainties in the link between climate change and flood risk. There is uncertainty at three levels:

- Future emissions. Since global warming is caused by the accumulation of greenhouse gases in the atmosphere, the degree of future warming will depend crucially on the future emissions of greenhouse gases. These emissions will depend, in turn on a combination of factors including future economic and demographic change, decisions by policy makers about mitigation instruments like carbon pricing, and technological progress in low-carbon technologies. Currently, climate policies around the world are expected to result in about 3.3°C warming above pre-industrial levels (Climate Action Tracker, 2018).

- Climate sensitivity. There is uncertainty over the precise sensitivity of the global climate to emissions and on how changes to the global climate will be reflected in local rainfall or sea-level rises. To illustrate, Figure 1 highlights the sea level rise around Edinburgh for three different emissions scenarios. Within each scenario, there is significant uncertainty, which increases as time goes on so that by 2100, it is plausible that sea level rise might lie between 10cm (5% probability in the lowest emissions scenario) and 80cm (5% probability in the highest emissions scenario).

- Economic exposure. The level and spatial extent of future economic development is uncertain, as is the vulnerability to flooding of future modes of production and exchange, which may involve novel technologies.

Figure 1. Multiple sources of uncertainty compound when considering climate-change impacts on flood



Notes: Figure shows Sea Level Rise (SLR) anomaly under three scenarios of emissions trajectories near Edinburgh. Solid line shows central estimate, shaded areas shows 5th to 95th percentile estimates. RCP 2.6 is a low emissions scenario, resulting in an increase in global temperatures of around 2°C relative to pre-industrial levels. RCP 8.5 is a high emissions scenario, resulting in global warming of over 4°C. RCP 4.5 is an intermediate scenario (Met Office, 2018)

Source: UKCP18, Vivid Economics

More will be learnt about the effect of climate change and flood risk over time. Three main sources of learning are discussed in the literature: information arising from progress in climate science, new hydro-meteorological observations, and incident-based learning(van der Pol, van Ierland, & Gabbert, 2017). Information from scientific progress includes better climate science and higher resolution climate models which are better able to resolve local climate phenomena. New hydro meteorological observations of peak river flows and sea levels can provide statistical evidence for changed flood risk. However, natural variability means that even decadal scale changes might not represent changes in long-term averages so a degree of residual uncertainty will always remain. Finally, incident-based learning refers to observed flood events which allow for flood probability estimates to be updated.

Managed adaptive approaches to flood risk management can produce greatly improved outcomes where, as in Scotland, there is uncertainty and anticipated learning on risks. A managed adaptive approach is a plan for managing flood risk, made up of a series of actions that might be taken at various points in time. The flexibility built into such a managed plan allows flood risk management measures to adjust efficiently as the future unfolds and more information on risk becomes available. Adaptive approaches can improve significantly on traditional 'predict then adapt' methods, which tend to implement capital intensive solutions that are expensive to modify and may turn out to provide a sub-optimal level of protection (Gersonius, Ashley, Pathirana, & Zevenbergen, 2013).

However, while Scottish regulatory guidance recommends the consideration of adaptive planning, the approach has yet to be implemented systematically. SEPA and the responsible authorities are directed to promote adaptive approaches (Scottish Government, 2019), but most plans do not consider adaptive schemes and none has explicitly recognised the value of flexibility that stems from climate uncertainty.

1.2 Scope of work and methods

Vivid Economics and HKV were engaged by ClimateXChange to understand the potential for and barriers to the adoption of managed adaptive flood risk planning in Scotland.

During Phase 1 of the project, the team carried out a review of international evidence on best practice in adaptive flood risk management, reviewing academic and 'grey' literature and including a series of detailed international case studies. The team gathered evidence on current practice in Scotland through a review of legislative requirements and regulatory guidance, interviews with practitioners including representatives from JBA Consulting, SEPA and Scottish Water, through a workshop specially convened at the Scottish Flood Risk Management Conference 2019 and through an on-line survey. This suggested a set of barriers to the more widespread adoption of managed adaptive planning in Scotland and a set of possible Scottish case studies. A selection of case studies was made in consultation with the steering group.

Phase II then examined these case studies in more depth, reviewing flood studies, carrying out interviews and basic modelling in order to highlight the value and feasibility of adaptive planning across a range of settings. On the basis of the findings of the case studies, and building on conclusions from the Phase I work, the study set out recommendations to develop SEPA's guidance in order to appropriately promote adaptive planning.

A glossary can be found in Appendix 5 on page 47.

2 Economic appraisal of adaptive plans

This Section sets out how economic appraisal can be carried out under conditions of uncertainty over future risks and how adaptive plans can be used to respond to that uncertainty. Section 2.1 introduces economic appraisal and explains how 'traditional' approaches can lead to suboptimal decision making where there is uncertainty, while Section 2.2 introduces the elements of an adaptive plan that can be used in managed adaptive flood risk management.

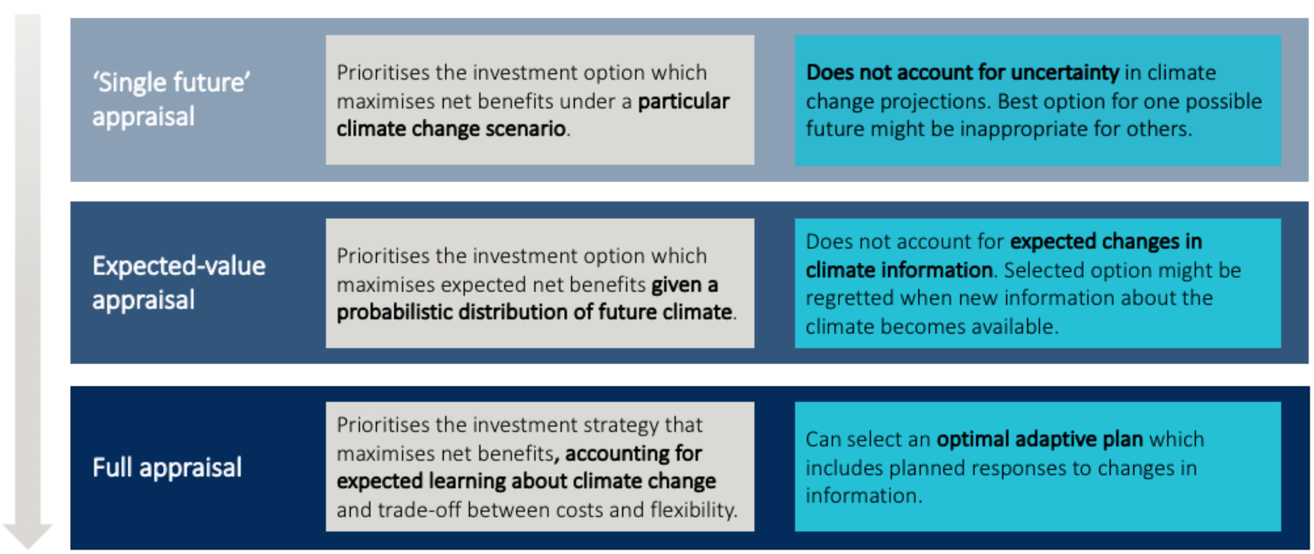
2.1 Economic appraisal with uncertainty and learning

Economic appraisal aims to achieve value for money, either by promoting schemes that produce the greatest net benefits (accounting for exceedance curves, risk preferences and investment costs, delivering optimal standards of protection that may vary over space and time) or by meeting fixed standards of protection for the least cost. Cost-benefit analysis, which is widely applied in Scottish flood risk management planning, assesses the ratio of a scheme's benefits to its costs, producing a 'Benefit-cost ratio' (BCR). A BCR of above 1:1 indicates that a scheme has benefits higher than its costs and is thus taken as the threshold for economic feasibility in this context (Scottish Government, 2015b).

Traditional applications of cost-benefit analysis do not account for uncertainty about climate change and anticipated learning about that uncertainty. A traditional 'single-future' appraisal assumes that the future risk conditions are known and prioritises the investment option which maximises relative benefits under a given climate change scenario. However, this does not account for uncertainty in climate change projections. As a consequence, the 'optimal' investment option under the single climate change scenario used in appraisal might turn out to be suboptimal under the outturn climate scenario.

A 'multiple future' appraisal recognises the uncertainty around the future climate but does not account for learning over time. Such an approach prioritises the investment options which provide the highest expected relative benefits given a set of probabilistic beliefs on the distribution of the future climate scenarios. As with traditional approaches, however, this does not account for expected changes in climate information: the selected option might represent an over or under-investment once more is learnt about future climate.

Figure 2. Different economic appraisal methods



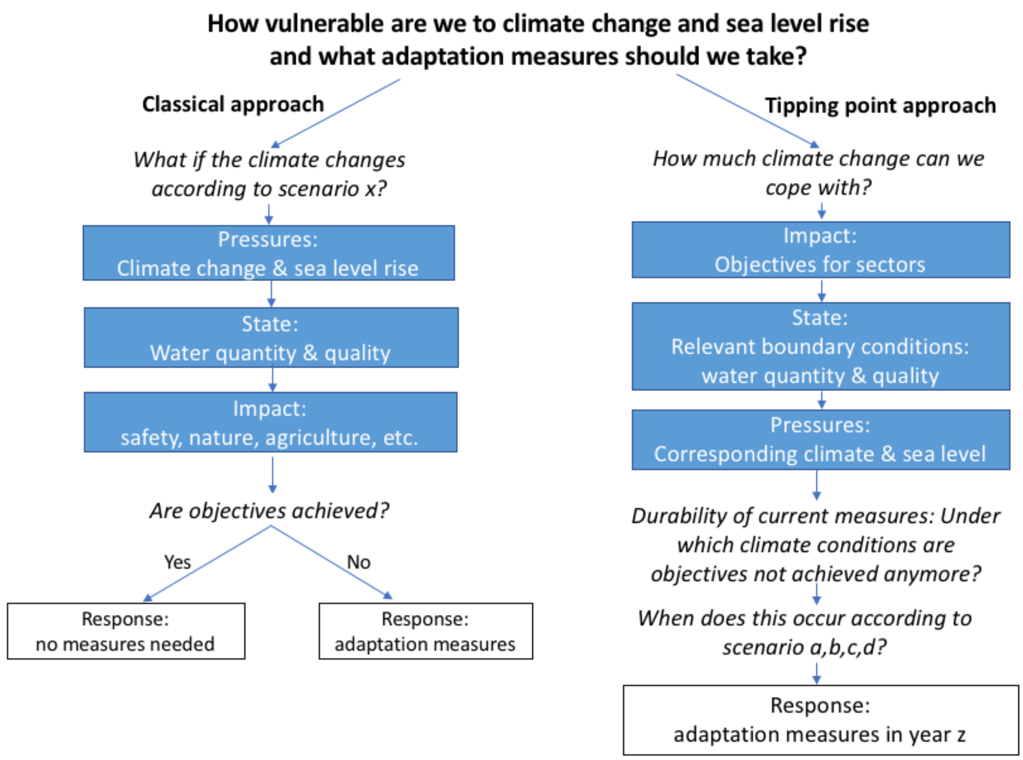
Source: Vivid Economics

A fuller appraisal can capture the benefits of flexibility by considering scenarios that unfold over time. Such approaches anticipate the fact that future FRM planners will have more information on the true climate scenario and will thus be able to adapt better than current FRM planners can *provided* current actions allow for future flexibility. The benefit of this flexibility is equal to the expected benefits of improved decision making in the future, while the costs of flexibility may involve construction costs (for example, the cost of building a sea wall with a higher base than is needed to meet the objective for current protection) or costs in terms of lower protection whilst a plan is being implemented. Single-future or expected value cost-benefit appraisals will account for the costs associated with flexible solutions but not for the benefits that flexibility brings.

2.2 Adaptive plans

Adaptive plans set out sequences of multiple actions and set tipping points at which actions change. Adaptive plans are built around the idea that, in times of uncertain future risk, flood defences may turn out to have a 'shelf-life'. For instance, a sea wall providing defence against coastal flooding might cease to offer the desired standard of protection if sea levels rise by 20cm. The point at which a measure is no longer meeting its objective, whether this be to provide best value for money or to offer a target level of protection, is referred to as a 'tipping point'. Alternative actions that better meet the objective are implemented by the time such tipping points are reached, taking into account lead times where required. This ensures that the desired standard of protection is always reached. Figure 3 below shows how the 'tipping point' approach followed in adaptive plans varies from the 'classical' single future or multiple-future approaches. Whereas the classical or multiple-future approach aims to identify what happens under given climate-change scenarios, the adaptive plan using tipping points identify how much climate change can be coped with.

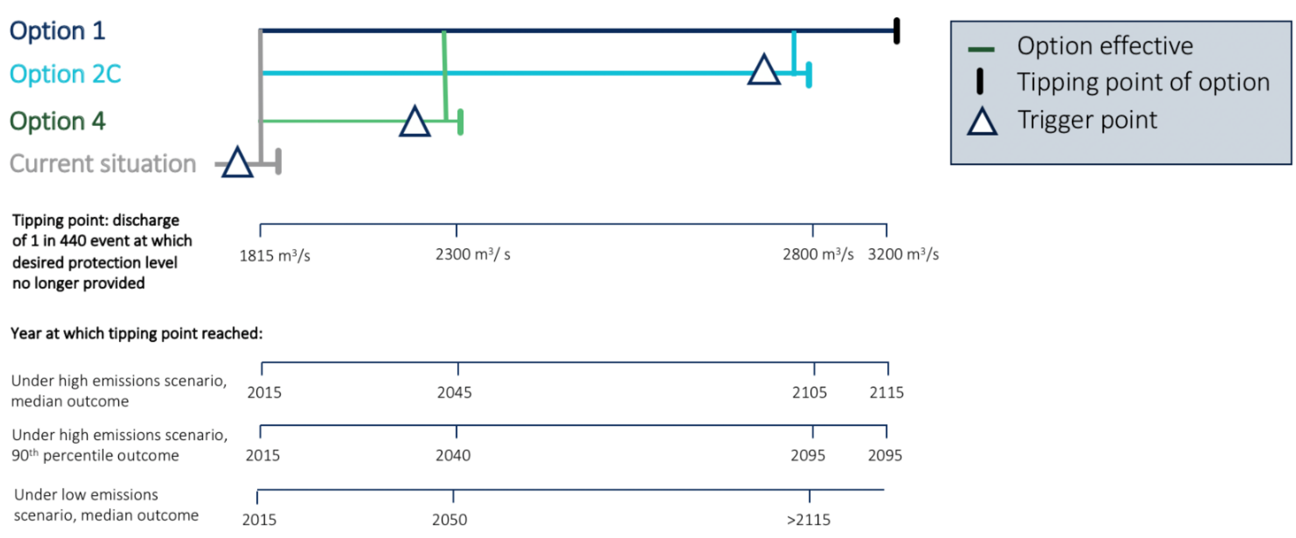
Figure 3. Tipping points represent a non-classical approach to flood-risk management under climate change



Source: Kwadijk et al., 2010

Tipping points can be used to *define* adaptive plans, as under the 'Dynamic Adaptive Policy Pathway' (DAPP) approach. This defines potential 'pathways' of actions around tipping points that can be considered in an economic appraisal. An example of DAPP planning from New Zealand is shown in Figure 4(Lawrence & Haasnoot, 2017). Here, an objective was set to provide flood defences to deliver and maintain a standard of protection of 1 in 440 years over the next 100 years. The discharge of the 1 in 440 year event is expected to increase over time with climate change. Actions were sought to meet this objective, as shown in Table 2, and each option was assessed to identify tipping points: that is, the magnitude of the 1 in 440 event, measured in cumecs, at which the option was no longer able to provide the desired standard of protection. By creating a deep river channel and a high berm, Option 1 provides the required standard of protection throughout the 100 year period, regardless of future climate scenario. Option 4, a smaller river channel, stops providing the desired level of protection by 2040-2050 (with timing dependent on the climate scenario). Option 2C meets the objective until the end of the period under the low emissions scenario but reaches its 'sell-by-date' after 80 years in a high emissions scenario. There are various opportunities to change between options. For example, a decision-maker can move to Option 1 or to Option 2C once Option 4 reaches its 'sell-by-date'. Given these opportunities to change between options, any given route through the map is a possible plan. In the example in Figure 4, there are a total of seven routes through the map and therefore seven potential plans. These plans can be appraised and compared in order to arrive at a preferred plan, which is then implemented. The figure also demonstrates trigger points: the points at which a decision maker will need to decide to move between options, taking into account lead times, in order that the desired standard of protection is always achieved.

Figure 4. Example Dynamic Adaptive Policy Pathway map



Source: Vivid Economics based on Lawrence & Haasnoot, 2017

Table 2

Option	Description	Cost
1	A 90m river channel and 50m berm	$267m
2C	A 90m river channel with 25m berm; properties to be purchased	$143m Staged to 4: additional $68m
4	70m river channel	$114m until 2035

Source: Lawrence & Haasnoot, 2017

Real options analysis can assess the value of alternative adaptive plans and select between them (Woodward, 2011). Real options analysis assesses the costs and benefits of each potential action under each relevant climate scenario and, by assigning probabilities to the climate scenarios, can compute the expected value of any adaptive plan. This fully accounts for the value of flexibility by assessing the expected benefits of future flexible decision making and the likelihood of exercising this flexibility. In the academic literature, real options analysis has been implemented using Monte Carlo simulation techniques or binomial decision trees (Buurman & Babovic, 2016; Deng et al., 2013). In practice, real options analysis has been applied to evaluating adaptive plans for water resource management and flood risk management (e.g. Baker, Hamm, Ash, & Sukthaworn, 2012; Haasnoot, Warren, & Kwakkel, 2019).

3 Implementation of managed adaptive planning

This section shows how managed adaptive planning has been implemented in international practice. This considers the exigencies of real-life investment decision-making processes, which create challenges for implementation. This section provides evidence on how these challenges have been overcome in international case studies, some of which are described in more detail in Appendix 6.

Table 3 sets out a stylised decision-making process and the key challenges that arise in each stage, used to structure the discussion in this section.

Table 3 Stylised decision-making process

Section	Key challenge
Section 3.1: Setting objectives for flood risk management	Must consider future risk sufficiently broadly
Section 3.2: Developing adaptive plans	Must consider multiple actions and how they can be combined
Section 3.3: Economic appraisal of adaptive plans	Must use suitable appraisal method
Section 3.4: Implementation of adaptive plan	Must provide for long term funding and monitoring

Source: Vivid Economics

Section 3.1 considers the first step, in which the purpose of a flood-risk management intervention is set. If the purpose is defined too narrowly or with reference to present day or a single climate scenario, adaptive planning might be discouraged.

Section 3.2 reviews a subsequent process of optioneering and screening, in which potential actions to meet the objective are developed: it is here that adaptive plans are created. The generation of adaptive plans involves consideration of multiple actions and how they can be combined into pathways.

Section 3.3 then looks at economic appraisal. This selects the plan (or action) that provides the best value for money whilst meeting the objectives set. It is crucial that an economic appraisal technique that accounts and values flexibility is used, otherwise adaptive plans might be rejected in favour of more traditional measures.

Finally, Section 3.4 reviews how an action or plan will be implemented. This requires processes for long-term funding, monitoring of the environment and community engagement.

3.1 Setting objectives for flood-risk management

In order for adaptive planning to be implemented, objectives must recognise the benefits of flexibility. The critical challenge is to do this in a straightforward manner that can subsequently be implemented in a transparent fashion. In England and Wales, the Environment Agency provides examples of objectives which might prevent or facilitate adaptive risk management(Environment Agency UK, 2018). Examples of definitions which might inhibit adaptive solutions include “to maintain the standard of protection through increasing the height of flood defences” or “to reduce the risk of flooding to a specific town by raising flood walls above expected climate change levels”. In the first case, the specification of “raising the height of flood defences” rules out other potential measures to reduce flood risk. In the second case, the objective sets a precautionary approach which encourages building to a high-level.

Examples of objectives that promote adaptive planning make direct reference to flexibility or the need for actions to be considered against multiple future climate change scenarios. For example, in the development of flood risk management plans in Hawke’s Bay in New Zealand, a dual objective for actions was used: to manage exposure to flood risk and to provide flexibility to respond to change in risks over time(Lawrence, Bell, & Stroombergen, 2019). Adaptive plans can also be supported by objectives to maintain a standard of protection into the future, explicitly recognising dynamic uncertainty over climate change. This was the case in the definition of purpose of the Thames Estuary, where adaptation options were sought that would provide a continued given standard of protection as the climate changes(Ranger, Reeder, & Lowe, 2013).

3.2 Developing candidate adaptive plans

Given appropriate objectives, three steps are involved in developing an adaptive plan:

1. Identify candidate measures for inclusion in the pathways
2. Determine tipping points of candidate measures
3. Assemble candidate plans by combining and sequencing candidate measures, screening out unviable options. Note that candidate plans may include inflexible measures.

3.2.1 Identify candidate measures

Here, individual actions are sought that might form part of an adaptive plan. This faces two key challenges:

- The pressure to seek only long-term measures that offer a high standard of protection with a single view of future climatic conditions. The literature identifies two kinds of pressures: the cost of generating scenarios to explore the full risk profile; and the political, regulatory and cognitive pressures to ‘create’ certainty(Lawrence et al., 2013).
- The use of screening processes that might prematurely reject measures which seem costly when considering any single climate scenario. Typically, appraisal processes involve making use of screening in order to reduce a long-list of potential measures to a shorter list which can be subjected to a full economic appraisal. The process is designed to remove potential measures that face insurmountable technical, legal or economic barriers early. However, this process might screen out measures which, although unviable on their own (for example, because they fail to provide long-term protection), might form part of a feasible adaptive plan.

International guidance, such as in England and Wales, provides examples of such measures for different types of flood risk(Environment Agency UK, 2018), covering both structural and non-structural options, as shown in Appendix 4. Wide stakeholder engagement and involvement of the community can also aid in producing a comprehensive set. According to best practice, the process should aim to identify candidate measures which are no-regrets (that is, they deliver benefits regardless of future scenario) and low-regrets (that is, they work well under most future scenarios and do not involve large costs under any scenario) and win-win (that is, they contribute to flexibility whilst having other, wider, benefits).

The use of multi-criteria decision analysis can help to ensure that a range of adaptive measures are considered for inclusion in candidate adaptive pathways. Multi-criteria decision analysis is a methodology used to evaluate and compare measures which vary across many attributes. Measures are evaluated against multiple pre-determined criteria. In this case, criteria could include flexibility and path dependency. Testing measures against these criteria can also help prompt changes to the measures which might make them more adaptive. An example of this methodology being applied is provided by The Environment Agency, which has developed a spreadsheet based multi-criteria analysis tool which can be used for this purpose (Brisley et al., 2018). Suggested criteria for inclusion of a multi-criteria decision analysis of potential measures are provided as follows:

- Reducing vulnerability
- Making space for water and function
- Delivering co-benefits and co-funding
- Building in flexibility
- Deferring, removing or abandoning

3.2.2 Determine tipping points of candidate measures

Once candidate measures have been developed, the tipping points of these should be identified. This might be the level of local sea-level rise at which a sea wall ceases to provide a 1 in 100 year standard of protection or the change in peak flow at which river defences are deemed inadequate. The identification of thresholds through modelling and simulation is a current topic of academic research. For example, Haasnoot et al.(2015) make use of an ensemble of synthetic time-series, a rainfall generator and a 'transient delta change method' to determine tipping points in sea level, precipitation and evaporation. However, since such methods are likely to be computationally and time intensive and require detailed hydrological modelling, tipping points can also be assessed using expert opinion.

The timing of these tipping points should be identified. It is not necessary to calculate or predict these exactly, but they should be bracketed such that they are roughly correct, for example 'on average the tipping point will be reached within 50 years, at earliest within 40 years, and at latest within 60 years' (Marjolijn Haasnoot, Kwakkel, Walker, & ter Maat, 2013). These timings can be generated by linking climate change scenarios with conditions (using outputs of climate models to determine when sea-level rise is expected to reach a given level under each scenario), or by simulation studies. Again, expert opinion can be used in order to lessen the computational burden.

3.2.3 Develop adaptive plans

Once potential adaptation measures have been found and their tipping points identified, these can be combined into a complete adaptive plan by determining signals that provide evidence of tipping points being reached and the trigger points at which these signals might be responded to. The trigger points and signals must include sufficient lead times to allow adaptation before the tipping point has been reached. Stephens et al.(2018) develop an approach using total storm-tide water level to design signals in each ten-year period.

Computer assisted approaches can also be used to develop adaptation pathways (Kwakkelet al, 2014), although these are likely to only be suitable for larger projects. Plans can, for simplicity's sake, be developed as a sequence of short-term (20 years), medium-term (20-50 years) and long-term (50-100 years) options, as in the case of the application of dynamic adaptive pathways to the Hawkes Bay, New Zealand (Lawrence, Bell, & Stroombergen, 2019). This approach has been used to overcome the large solution space and therefore required computational complexity created by the large number of possible climate futures and multiplicity of plausible actions that could be taken.

It might not be feasible to carry out a full economic appraisal of all the adaptive plans produced during this process. If this is the case, a process of screening can be applied to select a short-list of plans for full economic appraisal. Multi-criteria decision analysis can be used for this purpose to compare plans and select a smaller set for full economic appraisal.

3.3 Economic appraisal of plans

Decision trees represent a practical way of implementing real options analysis to carry out a full economic appraisal. First, an adaptive pathway map is transformed into a tree; nodes in the tree correspond to the trigger points (points at which policy makers might choose to take adaptation actions) and points at which new information about the climate might be available (signals). Having laid out the map as a tree, each route through the tree can be evaluated using traditional cost-benefit methods: valuing the stream of benefits versus the stream of costs, appropriately discounted, in order to generate a benefit-cost ratio.

The following information is required to carry out such a decision tree analysis:

4. A definition of future climate scenarios.

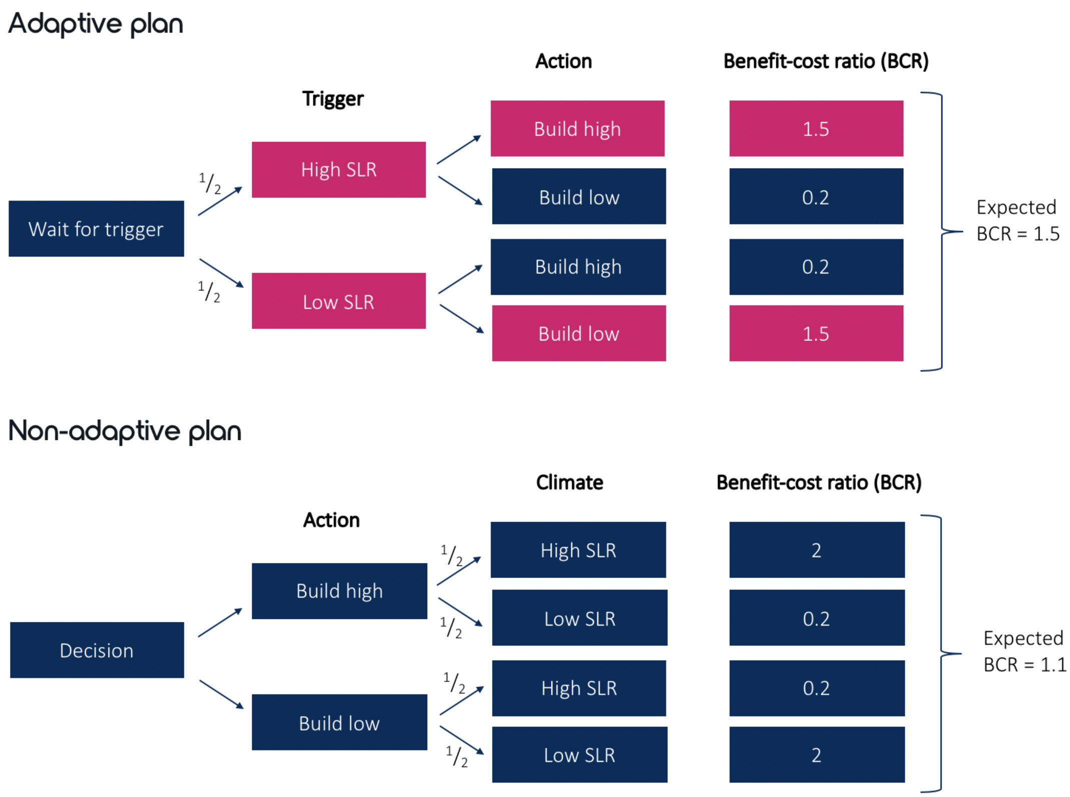
5. Benefits of each potential measure under each scenario. In practice, this means calculating expected flood damages under a range of climate scenarios.

6. Weights or probabilities of each future scenario. In reality, probabilities over the various climate change scenarios are not known. Guidance in England and Wales suggests applying equal weights to each scenario in the absence of known probabilities.

7. Investment costs for each of the potential measures. These can be estimated by traditional methods.

A simplified example of this type of analysis is shown below in Figure 5. Here an adaptive plan is appraised under two climate change scenarios, high and low, which are assumed to be equally likely. The tree ‘branches’ at decision points and at the realisation of the climate scenario. For each end point of the tree, the Benefit Cost Ratio is calculated. The BCRs are then weighted according to the probabilities of reaching the end point of the tree in order to calculate the BCR of the overall plan.

Figure 5 Simplified example of using real options analysis to compare non-adaptive and adaptive planning



Note: Probability of each climate change scenario assumed to be 50%. SLR refers to Sea Level Rise.
Source: Vivid Economics

3.4 Implementation of adaptive plans

In contrast to classical approaches, managed adaptive planning can be costly and complicated to implement over time. To implement managed adaptive planning requires:

- Monitoring of signals to verify trigger points. As exemplified in New Zealand, elements of a successful monitoring framework should include: general agreement on what is to be monitored and how; justification for monitoring; long-term consistency, so that changes over time will be detected; opportunities for public contribution to monitoring; and regular reporting (Bell, Lawrence, Allan, Blackett, & Stephens, 2017).
- A sufficiently stable funding environment which provides credibility that funding for future actions will be available when trigger points are reached. This could potentially be over time horizons of more than 100 years.
- Stakeholder support for more complicated plans. Guidance in England and Wales stresses the importance of stakeholder collaboration and engagement. In New Zealand, engagement with stakeholders through simulation 'games' that highlight the benefits of flexibility has successfully generated support for managed adaptive planning (Lawrence & Haasnoot, 2017).

4 Scottish guidance and practice

This section reviews the statutory framework, regulatory guidance and typical practice in Scottish flood risk management planning in order to understand the extent to which it meets the challenges set out in Section 3. Section 4.1 sets out evidence on the extent to which flood risk management planning in Scotland *is* adaptive, before Sections 4.2 to 4.5 probe in more detail how decision making functions at each of the four steps of planning described in Section 3. This forms the evidential basis for the conclusions on key barriers to more adaptive planning set out in Section 6. A more comprehensive review of guidance considered in this section is provided in Appendix 1. An overview of Scotland's Flood Risk Management decision-making process is also provided in Appendix 2.

4.1 Managed adaptive planning in Scotland

High-level guidance states that Flood Risk Management planning should be forward looking, acknowledges that future climate change risk is uncertain, promotes managed adaptive planning as a means for dealing with this uncertainty, and promotes the use of real options analysis for appraising climate-sensitive investments. SEPA and the responsible authorities are directed to avoid making decisions that will make it more difficult to manage the effects of climate change in future, in particular by not taking actions now which limit further adaptation in the future(Scottish Government, 2019).

However, this study was unable to find an example of a fully adaptive plan currently being implemented as part of the current planning cycle. Of 42 flood risk management schemes planned within the current planning cycle, we identified 25 schemes designed to provide a fixed standard of protection, of which 11 include an allowance for the future. None of the schemes planned are adaptive plans or make reference to multiple climate change scenarios. Two more adaptive approaches are currently under development and are considered in more detail in the case studies presented in the Appendix. In addition, an example was provided by one stakeholder of a flood protection scheme that was built with oversize foundations to allow for future adaptation, but where no trigger points, monitoring process or future adaptation plan was specified.

4.2 Setting objectives for flood risk management

In line with international best practice, guidance on economic appraisals directs SEPA and responsible authorities to consider the impact that potential actions will have on flood risk both now and in the future(The Scottish Government, 2016). In addition, actions should be 'adaptable to a changing climate and other drivers of changing flood risk'. In order to achieve this, objectives 'should be aspirational', that is, not set limits on what is feasible (The Scottish Government, 2016). Guidance explicitly warns against purposes which are narrow and makes reference to design standards, stating that a purpose such as 'to develop a flood embankment with a 1% annual exceedance probability (AEP) design standard' is not acceptable (Scottish Government, 2012).

The objectives set out in Flood Risk Management Strategies neither actively prohibit nor promote managed adaptive planning. A typical objective for a flood protection scheme is to "Reduce risk from surface water flooding", without making reference to any period or climate change scenario. As highlighted in Section 3.1, explicit reference to adaptive approaches or to multiple climate change scenarios in objectives might promote their uptake.

Comments received at Scotland's Flood Risk Management workshop suggest an adaptive mindset is not shared by all participants in flood risk planning. Discussions with practitioners highlighted that there is a widespread lack of comprehension of why adaptation is important and what it entails. This is reflected in the lack of adaptive measures in the flood risk management strategies.

4.3 Developing candidate adaptive plans

The Scottish flood risk management process requires a long-list of potential actions to be generated before full economic appraisal. Guidance states that managed adaptive approaches should be considered as a means to deal with flood risk, and that consideration should be given to a broad range of structural and non-structural actions(The Scottish Government, 2016). In order to aid this process, SEPA provides a non-exhaustive list of structural and non-structural actions that can be considered as part of a flood study (SEPA, 2018b). However, there is no specific guidance as to how these potential actions might be sequenced in an adaptive plan.

Guidance states that, because of the uncertainties in projections of future flood risk, it is preferable to take a 'no regrets' approach to managing future flood risk. This might include designing actions to take account of climate change now, or ensuring flexibility to enable adaptation in the future. However, the guidance also states that this 'may not be possible for large one-off interventions where building in climate change and other future adaptations at the start may be the only feasible approach' (The Scottish Government, 2016).

Some parts of guidance have been interpreted in a way that runs counter to adaptive planning. Scottish Ministers expect that actions that 'protect to a 1% exceedance probability plus allowances for climate change' be considered in all appraisals (The Scottish Government, 2019). Although design standards for actions are not specified, all decision-making processes are expected to consider a standard set of protection levels during the design process (1 in 200 years, 1 in 100 years and, 'if appropriate' a lower level) (Scottish Government 2019). In practice, this has sometimes been interpreted as an instruction to screen out measures which provide lower standards of protection, even though these might form part of an optimal adaptive plan in the short term. This is reinforced by methodologies in the 'Multicoloured Manual', which promotes the use of single climate change factors when estimating flood damages by recommending that scheme options are developed based on planning for the change factor covering the whole of the decision lifetime(Penning-Rowsell et al., 2013), without consideration of anticipated future learning about climate change impacts. Interviewees suggested that SEPA's 'Position on development protected by a Flood Protection Scheme' (SEPA, 2018c) encourages the construction of non-adaptive structural schemes providing a high standard of protection. SEPA deems it appropriate to construct houses and other vulnerable properties behind an existing or planned flood protection scheme only if a minimum standard of protection of 200 year plus climate change is provided. Local Authorities might thereby be encouraged to construct such schemes in order to facilitate new building activity.

Guidance on applying screening to adaptive measures is less well developed in Scotland than in other jurisdictions. Screening is suggested to reduce a long-list of potential actions to a more manageable short list. Three main criteria are recommended for screening out unfeasible actions – technical (removing options which are not technically feasible), legal (removing options which face insurmountable legal challenges) and economic (using professional judgement or 'light-touch' assessment of costs and benefits) to screen out actions where there is evidence that costs will exceed benefits. The Scottish Ministers' guidance on options appraisal suggests the use of a high-level scoring or matrix analysis for this process (Scottish Government, 2016). The guidance does state that potential for adaptation to climate change impacts should be included as a criterion when screening/shortlisting potential actions. However, this guidance is less developed than that for other jurisdictions; for example, the guidance in England and Wales provide examples of specific metrics for assessing the adaptability of an action (Environment Agency, 2018). In addition, the Scottish guidance does not provide prescription or suggestion as to how this criterion should be weighted against other important considerations.

In practice, adaptive actions are seldom if ever combined into an adaptive plan during the optioneering phase. Interviewees consulted during the course of this report stated concerns that the public and elected representatives do not understand or accept the benefit of adaptive plans. As a result, there is an unwillingness to include such adaptive plans in flood studies. Concerns were reported that adaptive plans which include a period of waiting for uncertainty to resolve or a period of accepting a lower standard of protection might be seen as an 'excuse for doing nothing'. Concerns were also reported that responsible authorities would receive criticism if a flood event took place during the implementation of an adaptive plan which could have been protected against by a precautionary adaptive measure. In addition, it was also suggested that responsible authorities are not yet used to 'thinking adaptively' and understanding the implications of climate change uncertainty for the schemes which they are designing.

In addition, it was reported that lack of Scottish guidance as to the tools and techniques that can be used to develop adaptive plans is a barrier to their use. In particular, there is a lack of guidance or examples about how to:

- Calculate expected damages under various climate change scenarios in order to identify tipping points;
- Design triggers which take into account long lead periods for construction of works;
- Create potential pathways out of the above.

This suggests that the lack of a standardised methodology is a critical barrier to developing adaptive plans. There is an absence of practical guidance as to how to develop adaptive plans, including the identification of trigger points and the development of adaptive pathways. This means there is a formidable methodological hurdle to be faced in implementing adaptive plans.

4.4 Economic appraisal of plans

The aim of economic appraisal in Scotland is to "stimulate the selection of the most sustainable solution by analysing the consequences of all options". This takes place at two levels: strategic appraisals (by SEPA) and full economic appraisals by responsible authorities. Guidance suggests the use of appraisal techniques such as cost-benefit analysis (CBA) and multi-criteria analysis (MCA) to calculate metrics which can be used to compare options against each other. In practice, cost-benefit analysis is in widespread use for full economic appraisals, but there is increasing use of multi-criteria analysis, of which cost-benefit analysis is a part, by SEPA at the strategic appraisal and prioritisation level.

Guidance for SEPA and responsible authorities on flood protection appraisals states that the effects of climate change should be taken into account during economic appraisals (Scottish Government, 2016). The guidance acknowledges that there is a large degree of uncertainty in climate change projections and suggests that a probabilistic approach 'might be applied' to assess future risk. Such an approach would be in line with international best practice, but the Scottish guidance does not provide further details on how this might be done in practice. In addition, the guidance is not clear as to whether such a probabilistic assessment should always be carried out or whether the use of a single climate scenario is also appropriate. In particular, it suggests selection of a climate change scenario based on the vulnerability of the receptors, with a more extreme scenario to be chosen when the receptor is expected to be more vulnerable, an approach the guidance describes as 'proportionate'. This can be interpreted as suggesting the selection of a single climate scenario.

Multiple climate change projections and probabilistic information under each of those projections is available for Scotland[1]. SEPA's Flood Modelling Guidance for Responsible Authorities currently summarises the available climate change information for surface water, fluvial and pluvial flooding as below. However, SEPA report that a future update of this document will take into account the latest scientific evidence.

- For surface water flooding, the guidelines recommends the use of uplifts in 'sub-daily duration rainfall depths' as per the UKWIR study for surface water flood studies and shown

[1] There is, however, no guidance on how to weigh the various scenarios.

in Table 7 in Appendix 3. This provides low, central and high projections during three epochs (2030s, 2050s and 2080s), although the low and high projections do not necessarily span the full range of potential changes. Without further elaboration, the guidelines recommend that “A risk-based approach should be adopted to make use of the high and low estimates.”

- For fluvial flooding, SEPA recommends use of the outputs of a CEH report on the vulnerability of Scottish river catchments to climate change. As part of this report, projections for rainfall and temperature from the UKCP09 projections were used to produce probabilistic estimates for change in river flow at the basin-level across Scotland. Similarly to the UKWIR study on surface water, these provide estimates for low, medium and high emissions scenarios and for three epochs (2030s, 2050s and 2080s), as shown in Table 8 in Appendix 3.

- For coastal flooding, UKCP09 makes projections of relative sea level rise available for three emissions scenarios (low, medium, high) and for the 5th, 50th and 95th percentile, high, as shown in Table 9 in Appendix 3. Projected sea level rises are provided annually up to 2100.

However, despite these multiple scenarios and probabilistic climate-change projections, there is no specific Scottish guidance as to how this climate change information should be used to appraise adaptive plans. Three approaches for using climate change information in economic appraisals are given:

- Using existing flood models

- Model changes in hazard in future periods. The guidance suggests calculating expected future flood damages at different various future time periods and using these to calculate benefit-cost ratios both with and without climate change. It makes reference to probabilistic approaches, but does not make precise recommendations on how to carry these out.

- Applied as part of sensitivity analysis when determining whether an option is economically worthwhile in high level strategic studies.

In practice, although international best practice suggests that multiple climate change scenarios should be used for making the business case for an action, economic appraisals in Scotland are often carried out under a ‘single future’ approach with a strong focus on benefit-cost ratios as the basis for decision-making. In particular, there is widespread use of a single climate change allowance when calculating the benefit-cost ratio of a given intervention; often this is a simple 20% uplift. For example, a flood study prepared for Dumfries and Galloway Council in 2016 considered five options to provide flood risk mitigation: three options (“property level protection”, “raised defences” and “raised defences with breached embankments in the downstream reach”) were deemed technically feasible. A 20% climate change uplift was applied ‘as per SEPA guidance’ to calculate benefit-cost ratios, which were then calculated with and without consideration of climate change[2]. Stakeholder feedback has indicated that such approaches are typical. In some cases, ways to make preferred action more adaptable are sought during the design phase. However, this approach is unlikely to result in optimal outcomes in comparison to consideration of adaptive plans all the way through the decision-making process.

As with the generation of adaptive plans, the lack of access to standardised methodology to apply economic appraisal methods to adaptive plans is a critical barrier to improved practice.

[2] Version 9.1 (June 2015) of SEPA’s “Technical Flood Risk Guidance for Stakeholders” stated that “SEPA recommends that a climate change allowance of +20% on the estimated 200-year peak flow be made”. This has been removed from later versions of the document.

This would include guidance on the specification of probabilities for scenarios and recommendations on the use of software or calculation methodologies.

4.5 Implementation

There is no guidance on the long-term monitoring, funding or implementation of managed adaptive plans. Funding for flood risk management activities is relatively short term, without a separate budget for funding or monitoring adaptive plans. Since 2008, the Scottish Government has allocated funding of £42 million per year for use by Local Authorities to deliver appropriate flood protection measures. This funding is available only for new schemes. 80% of the grant funding is allocated towards projects which have been prioritised as part of the Flood Risk Management Strategies, with the remainder used for other elements in the Strategies. Typically, this Scottish Government funding covers 80% of the capital costs of the measures, with 20% provided by the Local Authority. Scottish Government funding is guaranteed for 10 years from 2016 to 2026. This means that work currently being undertaken for the 2022–2028 cycle (for which Potentially Vulnerable Areas were designated in December 2018) is being carried out without certainty over the funding arrangements for the later part of the cycle.

The funding mechanism currently favours new, capital-intensive, inflexible schemes. Interviewees reported that, as Local Authorities effectively compete with each other for funding within a cycle, there is a tendency to promote larger, inflexible schemes that provide immediate and enduring protection rather than risk being 'outbid' in future windows. In addition, while central Government funding is available for new schemes, local authorities reported limited resources to fund operations and maintenance. Changes to the prioritisation process currently under development by SEPA could help to mitigate these problems, but the details of changes are yet to be confirmed. In addition, SEPA are proposing to include longer term plans in Flood Risk Management Strategies, which will include consideration of short, medium and long term actions.

Interviewees reported that Local Council maintenance budgets, which do not provide dedicated operation and maintenance funding, are too low to use for monitoring and reacting to new signals. Interviewees questioned whether the political support needed to maintain and implement adaptive pathways is present and will remain present, given short-term political cycles and local authority budgetary processes. The fact that Scottish funding arrangements provide local authorities with contributions towards capital but not operational costs, such as those related to monitoring, therefore acts as a further disincentive to adaptive planning.

The fact that funding envelopes are not set adaptively may further inhibit adaptive planning. As set out above, national strategic guidance, which explicitly endorses adaptive planning, does not present any structural barrier to adaptive flood risk management by RAs. However, there is a broader question of whether adaptive planning could be encouraged by making national flood risk management strategies explicitly adaptive, e.g. by making future funding envelopes contingent on emerging information on risks.

This could work in two ways:

1) By making the availability of future funding for RAs more credible, an adaptive strategy could incentivise adaptive approaches to planning.
2) An adaptive funding mechanism, which would include 'funding trigger points', could be used by RAs as a structure for developing more detailed adaptive strategies. This could be embedded in an iterative process, where indicative funding contingencies are set before the RAs develop plans, with strategies and plans then updated after plans have been reviewed and funding has been confirmed.

As with other issues related to funding, this is not taken forward to the recommendations in Section 7, but could be considered over the longer term.

Finally, a lack of experience in engaging the public on the benefits of adaptive planning presents a further barrier to implementation. Practitioners interviewed for this project reported that local residents tended to be resistant to adaptive plans where this resulted in delays in protection – or supportive only where this led to delays in construction or visual impacts of infrastructure. This points towards a lack of comprehension of – or confidence in – the adaptive planning, stemming from a lack of experience in engaging the public on plans of this type.

5 Scottish case studies

In order to test the prospective value and feasibility of adaptive planning across a range of relevant Scottish contexts, this project examined four Scottish case studies. Cases that were chosen exemplified efforts to carry out adaptive planning, or at least offered data that could highlight the benefit of doing so. Collectively, the case studies spanned coastal and river flooding in both rural and urban environments. Table 4 below shows how the case studies cover a range of relevant planning settings.

Table 4 Scottish case studies

Name	Description and relevance	Flood source	Environment
Clyde river corridor	Research has been commissioned by Climate Ready Clyde to develop outline adaptation pathways on coastal flooding for the Clyde corridor. This case study highlights the use of latest climate projections in developing adaptive plans.	Coastal, surface water, river	Mixed urban/rural
Stonehaven	Aberdeenshire council have commissioned a study to develop short, medium and long term options to manage current and future flood risk, including both structural and non-structural. This case study is an example of the development of adaptive planning within the framework provided by current regulation and guidance.	Coastal	Rural
Newburgh	An options appraisal for this coastal location found no current economic case for new defences, but that defences might become viable in the future if sea levels rise. This case study can be used to highlight the value of managed adaptive planning.	Coastal	Rural
Eddleston Water and Peebles	The Eddleston Water (a tributary of the Tweed) occasionally causes flooding in the towns of Eddleston and Peebles. The Eddleston Water Floodplain Project is a research project to understand how natural flood risk management can reduce flood risk and restore the natural environment. The case study demonstrates that, due to low capital costs and flexibility, natural flood risk management is typically amenable to inclusion in adaptive plans.	River	Rural

Source: Vivid Economics

Each case study is built up from a review of planning documents and data, a series of interviews, and some indicative modelling. Interviewees included local authority personnel and consultants engaged to develop management plans. Modelling, which was carried out for Newburgh and Eddleston, used existing data and simple assumptions to generate and 'solve' decision trees of the kind introduced in Section 3. Results from these modelling exercises are not intended to inform FRM planning decisions directly, but do show the potential value and feasibility of this kind of approach. Appendix 7 presents the case studies in detail, while the remainder of this section provides an overview of the findings.

The studies demonstrate that adaptive approaches are valuable in a variety of settings. In Stonehaven, Newburgh and the Clyde, flood studies show how sequenced interventions designed to adapt to profiles of increasing risk may offer greater value for money than 'once-and-for-all' investments. Furthermore, modelling in Newburgh and in Eddleston shows how more fully adaptive approaches where future interventions are *contingent* on future climate risks can yield greater value for money still. The case studies expose conditions where adaptive planning is particularly likely to add value:

- **Coastal flooding risk** lends itself more easily to adaptive planning than fluvial or surface water flooding, as it is more straightforward, given available modelling platforms, to understand how future trajectories of sea level rise can affect risks over time. As a consequence, adaptive planning in the Clyde and Stonehaven focuses on this source of uncertainty, even though future changes in other risks are also relevant.

- **Significant economic development**, as exemplified by the planned 'Growth Corridor' in the Clyde region, can reinforce the value of adaptive planning. There are two reasons for this. First, economic development enhances the value of flexibility in flood risk management strategies by adding a layer of uncertainty and anticipated learning: the scale, vulnerability and spatial profile of future economic development may all be uncertain, and therefore call for an adaptive response. Second, *credible* plans that respond to future development trajectories in an adaptive fashion provide useful signals to investors about the way in which flood risk for any development will be managed. This can incentivise more efficient decisions over how to develop, reducing the costs of flood risk management.

- **Natural flood management (NFM)** schemes, as are under development in Eddleston, are valuable elements in adaptive plans. NFM schemes can provide low-cost risk mitigation, that can be flexibly varied over time, making them well suited to adaptive plans, though certain types of scheme can have long lead times before they become effective.

- **Adaptive thinking**, where better value adaptive options are brought into consideration, can be prompted by an adaptive approach to planning. In the Clyde River Corridor, plans were built up around a structure of pathways of future risk, which informed the prioritisation of short-term low- or no-regrets interventions before more information was available. In Stonehaven, a similar framing of the flood risk management problem could have prompted greater emphasis on shorter-term measures such as property level protection.

Adaptive planning is feasible, even in small catchments where limited resources will be available for flood studies. In particular:

- **Modelling is feasible**. Adaptive planning does not necessitate very onerous or detailed modelling although more robust risk models will lead to improved decision making. The case studies highlight how modellers have implemented pragmatic workarounds in order to reduce the complexity of understanding future risks. This includes the use of indicative tipping points in the Clyde, the interpolation of risk information over 100 years in Stonehaven, and the simple definition of pathways of interventions in Newburgh. Work by this project and third parties demonstrates the feasibility of fuller real options valuation in the Eddleston catchment and Newburgh.

- **Capacity exists in the sector**. Where local authorities specify requirements for adaptive planning in the flood study terms of reference, consultants have shown an ability to deliver on this. This was the case in Stonehaven, a relatively small catchment facing significant and complicated risks.

However, the case studies exemplify limitations in the practice of adaptive planning that stem from barriers examined in Section 4. These include:

- **Narrow climate scenarios**, with Stonehaven and Newburgh studies using a single climate projection, assessed at the 95th percentile. As a consequence, the preferred options lack a full or representative account of future risks and do not consider the likelihood of various pathways of learning. To overcome this barrier, guidance could offer more concrete recommendations on suitable suites of scenarios and probabilities to apply to them.
- **The use of sequenced options rather than adaptive planning**. In the Stonehaven case study, a set of interventions to be made at given points in time were appraised rather than adaptive plans, in which future interventions are made contingent on trigger points. One barrier to the adoption of fuller adaptive planning is the narrow set of climate scenarios used to assess future risks, noted in the previous bullet; another is a lack of funding for the monitoring activities required to implement adaptive plans.
- **Stakeholder engagement**. None of the case studies has reached a phase of very significant engagement with stakeholders on adaptive plans, but interviewees expressed nervousness that the rationale for such plans would be difficult to explain.
- **Modelling limitations,** which affect classical as well as adaptive planning. These include difficulties in understanding how multiple hazards interact (such as in Stonehaven and the Clyde) or how catchment-wide dynamics affect risks (as in Eddleston).

6 Conclusions

Adaptive planning remains a novel approach to flood-risk management, internationally as well as in Scotland. This report has shown that adaptive planning can provide for more effective decision-making when future risks are uncertain, as is the case in a changing climate. Methods for the practical implementation of adaptive planning are still being developed by academics and other experts, but this report has shown examples of the method being applied internationally. However, the work has found little evidence of the full implementation of such approaches in Scotland, despite high-level guidance which promotes them.

Case studies show that the wider implementation of adaptive planning is both valuable and feasible across a range of settings. Flood studies in rural and urban areas, managing coastal and fluvial flooding risks, have shown that sequences of interventions as risks increase can offer greater value for money than once-and-for-all interventions considered in classical approaches to flood risk management. Modelling work by this project shows that more adaptive planning, where future interventions are made contingent on risk triggers, could offer better value for money still. The value of adaptive approaches is likely to be greatest in settings where significant economic development is expected and natural flood management interventions are important options. Furthermore, pragmatic approaches to modelling can allow these approaches to be appraised even in rural settings where resources for flood studies are likely to be limited.

This report has identified critical barriers to the use of managed adaptive planning in Scotland. They are:

- **The lack of a standardised methodology to generate adaptive plans.** There is an absence of practical guidance on how to develop adaptive plans, including the identification of tipping and trigger points and the development of adaptive pathways. This means that there is a formidable methodological hurdle faced in developing dynamic plans, which FRM planners seldom have the capacity or resources to overcome. By producing a standardised methodology, the costs and risks associated with generating adaptive plans could be significantly reduced.

- **The lack of a standardised methodology to economically appraise adaptive plans.** Even if adaptive plans were developed, there remains a hurdle in assessing the value of these plans and comparing them to traditional structural actions. A standardised methodology would include guidance on the specification of probabilities for scenarios and recommendations on the use of software or calculation methodologies.

- **Funding mechanisms, which disincentivise managed adaptive planning and promote large scale interventions.** This stems from two key features of the funding regime. First, in any FRM planning cycle, Local Authorities compete against each other for a fixed budget of central Government funds, without clarity around the level of funding in future funding cycles. Second, the large majority of the capital grant from central Government is allocated to large scale schemes, with local authorities reporting limited funding for operations and maintenance/adaptation of existing schemes. Together, this incentivises Local Authorities to promote new capital-intensive inflexible schemes which use central government funding – since such schemes are less 'risky' to deliver than adaptive plans where funding for future adaptation might be unavailable. An alternative model of funding in which both long-term national strategies and the supporting funding were set in an adaptive manner, consistent with local plans, could encourage more adaptive planning by RAs.

- **Planning boundaries.** Although Local Plan Districts follow catchment boundaries, detailed options appraisals are commissioned by Local Authorities, whose boundaries do not align with catchments. This means that catchment-level modelling of risks and mitigation options tends not to be conducted, inhibiting catchment level planning. This is of particular importance where natural flood management schemes are under consideration – as such schemes tend to produce benefits downstream from the intervention sites and are often more adaptable than other types of scheme.

Barriers related to planning boundaries and funding can be addressed without changes to guidance. In the first instance, greater emphasis on identifying opportunities for joint working could promote more holistic catchment-level planning, since all RAs would be expected to benefit from this. To better incentivise RAs to pursue adaptive planning through funding mechanisms would require policy changes that lead to the more even treatment of capital and operational expenses, and that match the funding horizon to the planning horizon through a credible commitment to future funding of adaptive plans.

Section 7 **below sets out recommendations on how guidance can be changed, supported by more research, to address other barriers.**

7 Recommendations

The recommendations set out below aim to address the barriers identified in previous sections and summarised in Section 6**.** They suggest more prescriptive guidance for the conduct of adaptive planning in economic appraisals, which could be adopted by RAs (Section 7.1) and two programmes of research that can develop this guidance further with quantified estimates of uncertainty (Section7.2). Potential changes to funding mechanisms or planning boundaries lie beyond the scope of this work, so are not considered in this section.

7.1 Process for generating and appraising adaptive plans in economic appraisals

This section sets out recommendations across the four phases of planning used throughout this study: setting objectives, developing options, appraising options, and implementing a plan. Nine key recommendations are highlighted within a supporting narrative.

Recommendation 1: Setting objectives

(1) If risk is sensitive to uncertain future climate and/or socio-economic scenarios, require this sensitivity to be accounted for in tenders for flood studies. In such cases, recommendations 2-8 below apply.

Where flood risks are expected to vary significantly between different scenarios of climate or socio-economic change or there is significant potential for locking in future risks, this should be reflected in scoping documents/Invitation for Tenders for options appraisals.

RAs should specify that a broad range of future climate risks, socio-economic scenarios and time periods are considered in any options appraisals study. If this is not specified, competitive pressures are likely to lead to options appraisals which only consider the minimum number of climate change scenarios.

Recommendations 2-5: Developing adaptive plans

(2) Options appraisal studies should assess risks and potential actions in whole catchment areas.

Where it has been deemed appropriate to develop adaptive plans in response to increasing future flood risk or socio-economic change, the following steps should be taken:

Identify candidate measures for inclusion in adaptive plans: The optioneering process should seek to find measures that provide protection against events of various severity, notably including smaller, more frequent flood events (events with low return periods) and those that are only likely to occur under more extreme climate change scenarios (events with very high return periods). These should include measures that reduce the likelihood of flooding (for example, application of NFM in catchments above assets at risk), options that directly protect assets (e.g. flood walls) and options that reduce damages if flooding does occur (e.g. property flood resilience, community awareness of warning schemes). In areas of high flood risk, candidate measures should also include managed withdrawal or retreat.

(3) In shortlisting interventions, follow a multi-criteria approach in which ‘adaptability’ is included as a criterion.

If too many candidate measures are identified to feasibly appraise in full, Multi Criteria Analysis should be applied in order to shortlist measures for more detailed assessment. It is important that measures are not prematurely excluded for not having a positive Benefit Cost Ratio under current or future conditions or for only providing protection against events with low return periods. The Environment Agency's spreadsheet based tool (Brisley et al., 2018) is an example of the type of tool that may assist with this. Criteria included in this tool are:

a. Reducing vulnerability

b. Making space for water and function

c. Delivering co-benefits and co-funding

d. Building in flexibility

e. Deferring, removing or abandoning

The appropriateness of this and other tools for the Scottish context should be assessed before any specific recommendations on the criteria to use are put forward.

(4) Identify trigger points, through the following steps:

I. Engage with the community to identify an 'acceptable' level of Average Annual Damages (AAD)

II. Assess climate risks under various scenarios to, identify tipping points at which AAD exceeds the acceptable level

III. Account for intervention lead times and planning cycles to specify trigger points at which decisions may need to be taken in order to avoid unacceptable levels of risk.

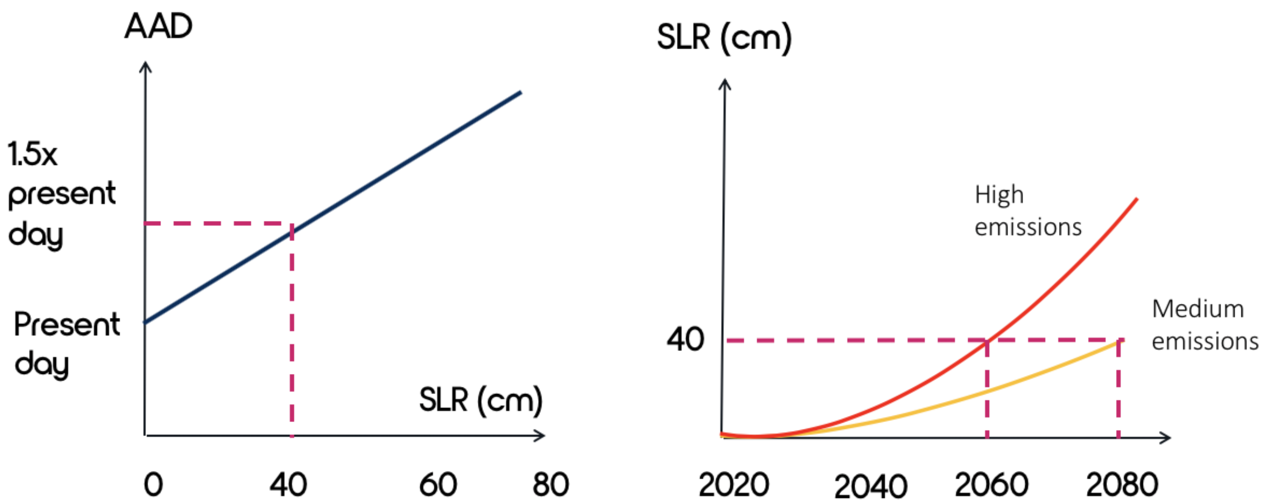
Tipping points refer to the point of climatic or other change where a candidate flood risk management measure does not meet its objective. For example, this might be the increase in sea level rise under which a sea defence no longer provides an adequate protection to the assets behind it. Two steps are required in order to identify tipping points, which are demonstrated in Figure 6 below:

i. **Determine an 'acceptable' level of risk, in terms of an acceptable level of Annual Average Damages**. For instance, it might be considered acceptable to allow risks to rise by 1.5 times relative to their present-day levels. The decision as to the acceptable level of risk depends on stakeholder preferences, and community engagement is recommended to determine acceptable levels of risk in any vulnerable area. As risks increase, it might not be feasible to continue to provide protection against 1 in 200-year flood events. In this case, early engagement with communities and stakeholders will be necessary to determine what level of risk is acceptable and what costs can be borne.

ii. **Estimate Annual Average Damages for range of a climate outcomes in order to determine at what level of climate change the tipping point is reached.** This will identify, for example, the level of sea-level rise (in centimetres) under which proposed coastal flood defences no longer provide the desired standard of protection or the peak river flow against which a fluvial defence is no longer providing the desired standard of protection. A practical challenge is modelling time required to estimate damages under a full range of possible climatic impacts (for example, under a full range of possible sea level rises). It is therefore likely to be necessary to estimate damages under a small number of possible climatic impacts and interpolate between these to identify the point at which the Annual Average Damages exceed their threshold level. Based on climate change information published by SEPA/the Met Office, the point in time at which the threshold might be exceeded under various climate change scenarios should then be identified.

iii. **Specify trigger points at which decisions may need to be taken.** The definition of trigger horizons can be matched approximately to the potential timings of breaches of tipping points (for example, in Figure 6, 2020-2060, and 2060-2080 are potential trigger points), but should also align with points in planning cycles at which decisions are made and account for lead times between these decisions, the implementation of any intervention, and the consequent increase in protection.

Figure 6. Determining tipping points and when those tipping points might be reached



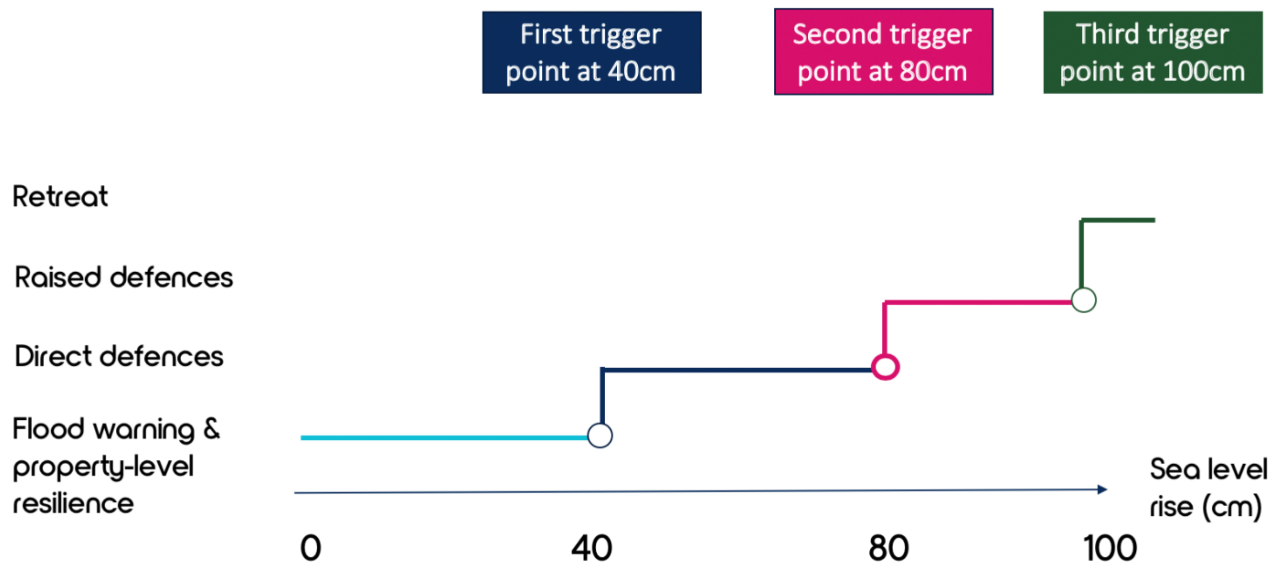
Note: Tipping point defined as a 1.5 increase in Annual Average Damages compared to present day is reached at 40cm of sea level rise (left panel). 40cm sea level rise is reached in 2060 under the high emissions scenario, and 2080 under the medium emissions scenario

Source: Vivid Economics

(5) Develop candidate plans, in which potential interventions are introduced at trigger points, contingent on scenario realisations. Plans must include 'do nothing' and 'do maximum' options.

The trigger points can be used to generate a small number of plausible plans as a sequence of short-term, medium-term and long-term measures. This reduces the computational complexity created by the large number of possible climate futures and multiplicity of plausible actions that could be taken. Typically, when sequencing candidate measures, measures which provide a lower Standard of Protection (for example, Natural Flood Risk Management and Property Level Protection) should be sequenced before structural measures which provide a higher Standard of Protection, taking into account the lead times that might be needed to implement them. Computer-assisted approaches including genetic optimisation algorithms can be used for larger studies where more assets are at risk and a large number of potential actions might be taken (Kwakkelet al., 2014). In both cases, a 'do nothing' and a 'do maximum' plan, which applies a precautionary approach, should be included for comparison.

Figure 7. Adaptive plan with three trigger points in terms of climate impacts



Note: Under this adaptation plan, property-level resilience and flood warning systems will be installed to respond to current risk. Defences will be built if sea level rises reach 40cm, and then raised if sea level rise reaches 80cm. At 100cm, properties might be relocated or population will retreat.

Source: Vivid Economics

Recommendation 6: Economic appraisal of adaptive plans

(6) Select plans based on an NPV criterion, where NPV is calculated using probabilities of all scenarios and Annual Average Damages under each scenario.

The economic appraisal of an adaptive plan involves calculating the value of the plan over the full appraisal period, taking into account uncertainty about the future climate and how the plan indicates a decision maker should react to new information. The process is illustrated in the figures below, where a plan to be appraised is set out in Figure 7. The plan is defined by carrying non-structural options until sea level rises 40cm, at which point defences will be built. If sea levels rise to 80cm, then the defences will be raised. The steps required to appraise this and other plans are as laid out below. For each plan, a Net Present Value (NPV) is calculated. This incorporates the uncertainty around future climate and the actions that the plan includes at each trigger point. Plans can be compared by carrying out this process for each plan, and comparing NPVs across plans.

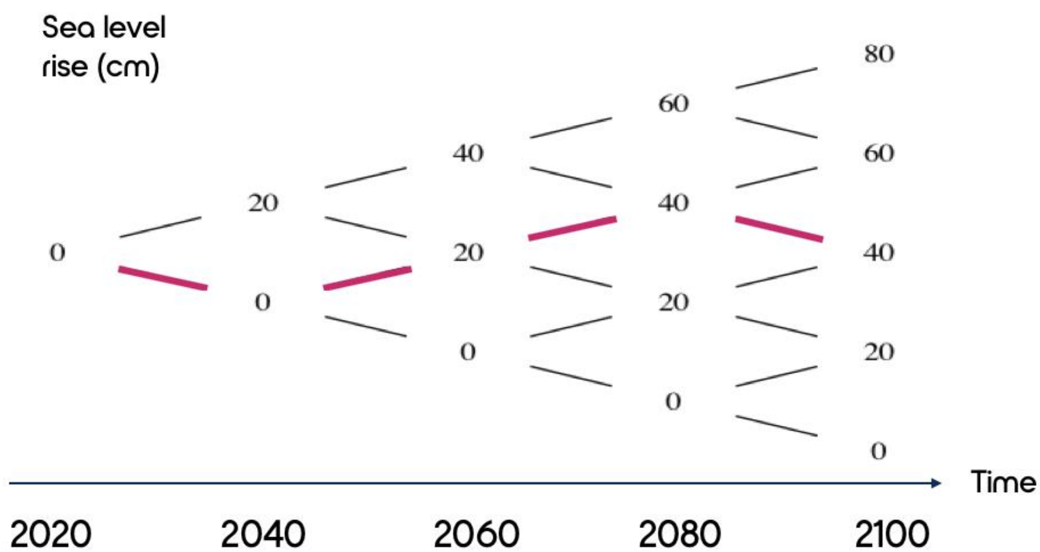
I. **Set out a tree of potential climate pathways based on published climate change information (Figure 7).** For larger studies, the Net Present Value of a candidate adaptive plan should be calculated over a fully probabilistic distribution of climatic realisations at a large number of time periods, taking into account uncertainties both between and within emissions scenarios. This is unlikely to be feasible for smaller studies, where the plan can be appraised under a smaller number of climatic realisations and time periods. A simple approach to create a climate pathway is to use a 'binomial lattice', as in Figure 8. A binomial lattice models the evolution of a climate variable across time, assuming that the climate variable can change in one of two ways at each time period. In the example, sea levels are modelled as either increasing 20cm (with probability 50%) or remaining constant (with probability 50%) in each time period, resulting in a distribution of possible 2100 sea level rises between 0 and 80cm.

II. **Assess the Net Present Value (NPV) of carrying out the plan under each one of the potential climate pathways (an example for one climate pathway is shown in Figure 8).**

For each potential climate pathway, the NPV of the plan should be calculated in the standard way, using information on costs and flood risk reduction benefits, taking into account the climate change pathway when calculating flood risk reduction benefits. In the figure, the NPV of the plan is being assessed under the assumption that the sea level rises to 20cm in 2060 and 40cm in 2080, and that the adaptation measures are carried out as planned with costs which are anticipated. This exercise should then be repeated for each other potential climate pathway.

III. **Integrate the NPVs across each potential climate pathway (Figure 9)**. Once the NPV has been calculated for the plan under each potential climate pathway, the results can be integrated by taking a weighted average of the NPVs under each climate pathway, with weights corresponding to the likelihood of each climate pathway. In the example, there are sixteen possible climate pathways, each with the same probability. The weighted average of the plan's NPV under each pathway is calculated. This is the NPV of the whole plan.

Figure 8. Step Two: assess the NPV of the plan under each climate possible pathway, by considering costs and benefits at each time period. Here, the NPV of the plan under the pathway in pink is calculated.



Period	Action	Costs	Damages	NPV damages plus costs (£k)
2020-2040	Install flood warning system and property-level resilience	Build costs	Damages with flood warning and property-level resilience at 0cm SLR	*CALCULATED*
2040-2060			Flood warning and property-level resilience damages at 20cm SLR	*CALCULATED*
2060-2080	Build lower defences	Build costs	Lower defences damages at 40cm SLR	*CALCULATED*
2080-2100			Lower defences damages at 40cm SLR	*CALCULATED*

Note: The NPV of the plan is assessed under the assumption that SLR rises to 20cm in 2060 and 40cm in 2080, highlighted in pink

Source: Vivid Economics

Figure 9. Step three: Integrate NPVs across climate pathways

3. Integrate NPVs across climate pathways

SLR 2020 - 2040	SLR 2040 - 2060	SLR 2060 - 2080	SLR 2080 - 2100	Probability	NPV of damages plus costs (£k)	Weighted NPV
0	0	0	0	1/16	*CALCULATED*	*CALCULATED*
0	0	0	20	1/16	*CALCULATED*	*CALCULATED*
0	0	20	20	1/16	*CALCULATED*	*CALCULATED*
0	0	20	40	1/16	*CALCULATED*	*CALCULATED*
…	…	…	…	…		
					Total:	*CALCULATED*

Note: There are sixteen possible climate pathways, each with the same probability. The NPV of the plan under each one is calculated, and the average NPV is calculated. This is the NPV of the plan.

Source: Vivid Economics

Recommendations 7 & 8: Implementing plans

(7) Set up necessary monitoring processes in order to verify trigger points.

The implementation of adaptive plans requires the ability to verify trigger points. To execute an adaptive plan requires monitoring processes, potentially including equipment, that can verify trigger points and prompt a response as set out in plans. RAs should therefore include monitoring strategies in any adaptive plans and account for any associated costs in NPV calculations.

(8) Maintain risk models within RAs so they can be updated at low cost as new information becomes available.

RAs should maintain modelling platforms in order to update adaptive plans at low cost. Flood Risk Management Plans are reset every six years on the basis of new information, potentially including relevant climate and development scenarios as well as the availability of new options. Where plans are adaptive, this process of reappraisal should test whether conclusions on the optimal adaptive pathway still hold in light of this new information. To reduce costs, RAs should ensure that models created for Flood Studies are retained so that they can be cheaply rerun once new information is available.

7.2 Recommendation for further research

This report has identified the need for two further pieces of research to inform guidance. By commissioning or carrying out this research, the Scottish Government would provide planners with greater clarity on how to meet technical challenges involved in adaptive planning, hence reducing its costs. They would also promote a degree of consistency in the way RAs implement adaptive planning that would make plans more comparable and could assist in the formulation of adaptive strategies at a national level.

The first piece of research would develop a standardised methodology for assigning probabilities to scenarios used in planning. Current practice in most appraisals is to consider one or two climate change scenarios, applying 100-year climate change uplifts which are “unlikely to be exceeded” (in the case studies, the 95th percentile impacts) when estimating future flood risks. For example, a 100 year 95th percentile sea-level rise under the ‘medium’ emissions scenario is often considered in coastal flood studies alongside present-day conditions. This provides an unbalanced view of climate change impacts. Instead, the Scottish Government and SEPA could develop and promote:

- a more representative set of climate scenarios, better capturing the uncertainty in future climate projections and the associated range of possible climate change outcomes;
- a standardised means to combine scenarios, leading to a single probability distribution of climate change impacts on combinations of sea level rises/peak river flows/extreme rainfall; and
- guidance on how to set pathways, which specify *both* the uncertainty the planner faces at any point in time under any scenario *and* the future learning the planner anticipates from that point(‘transition probabilities’). The pathways should cover the whole planning horizon (100 years) and include decision points at least every 20 years.

The second piece would specify guidance to estimate damages under different scenarios. Effective adaptive planning requires understanding of how risk levels change throughout the planning horizon, under a large number of climatic futures (for example, over a range of sea-level rises). However, computational complexity means that it is not currently feasible to carry out detailed hydrological modelling and damage assessment for each possible outcome of sea-level rise, increase in peak flow or increase in high intensity rainfall, at each point in the planning horizon. This might change as hydrological models improve and processing power becomes more abundant, but in the meantime, research is required on how to efficiently estimate expected damages for a continuous range of sea-level rises/peak river flows/changes in extreme rainfall. In some cases, a simple linear interpolation between a ‘current day’ and ‘extreme future’ climate might be appropriate; however, whether this is appropriate will depend on the hydrology in the area of interest. SEPA and/or the Scottish Government could use the outcomes of this research to produce guidance on identifying how many climatic futures damages should be modelled and how to extrapolate between these.

Appendix 1: Guidance on use of climate change projections in economic appraisals

Table 5 Guidance on use of climate change projections in economic appraisals

Document	Summary and/or relevant extracts pertaining to climate change information in appraisals and managed adaptive approaches
Local Authority flood study checklist, Version 3(SEPA, 2018b)	• 'Do nothing' and 'do minimum' options should include assessment of climate change. • Provides a list of potential structural/non-structural Flood Risk Management options, however, these do not specify inclusion of adaptive plans or options. • Managed adaptive approaches "(which can be adjusted as conditions change or new information becomes available)" should be considered. • "Potential for adaptation to climate change" and future flood risk drivers should be included in screening/shortlisting. • Recommends following methods set out in the Multi-Coloured Manual to carry out economic appraisal. • Where possible, actions should be developed with a 'no regrets' approach to managing future flood risk (for example, as a result of climate change). This might include designing actions to take account of climate change now, or ensuring flexibility to enable adaptation in the future. • References Environmental Agency guidance ("Accounting for adaptive capacity in FCERM options appraisal. (SC110001/R1)").
Multicoloured Manual (Penning-Rowsell et al., 2013)	• Use of change factors. • Recommended that scheme options are developed based on planning for the change factor covering the whole of the decision lifetime.
Treasury Green Book - Accounting for effects of climate change, (HM Treasury and Defra, 2009)	• Adaptation measures should be flexible. • Recommends use of real options analysis for appraising investment decisions which incorporate uncertainty, flexibility and learning potential.
Delivering Sustainable Flood Risk Management (Second edition, Feb 2019 update), (The Scottish Government, 2019)	• SEPA and Responsible Authorities must act 'with a view to reducing overall flood risk'. • SEPA and the responsible authorities should avoid making decisions that will make it more difficult to manage the effects of climate change. This will involve not locking in options that limit further adaptation in the future. • Scottish Ministers expect that options that provide protection to a 0.5%, 1% exceedance probability to be considered in all appraisals. • As an option we expect actions that protect to a 1% exceedance probability plus allowances for climate change to be included in all appraisals.

	• Actions to tackle flood risk should be planned to ensure that any short term actions are part of a coherent longer term plan (50 - 100 years) with a view to retaining sufficient flexibility to manage changing risks and societal changes over that period.
Flood Modelling Guidance for Responsible Authorities Version 1.1, (SEPA, 2018a)	• The guidance summarises the best available projections for climate change on sea level, flood flows in rivers and heavy rainfall that was available at the time it was published. Depending on flood source, projections are given for a range of emissions scenarios, probability levels and time horizon, but no guidance is given on how the range of values should be used in a flood study and the single scenario used in SEPA's flood hazard maps is highlighted. • Chapter 10 summarises available climate change information for changes in peak river flow, short duration rainfall, and sea level rise. These are as follows: • For pluvial floods, Responsible Authorities are recommended to use the uplifts from the UKWIR (2015) study for any future surface water studies as these are based on the latest science. A risk-based approach should be adopted to make use of the high and low estimates. [Note: an update to the UKWIR study was released in 2017]. • For coastal flood risk due changes in mean sea level, a risk-based approach should be adopted in using the UKCP09 sea level rise projections, but the medium emission scenario 50th percentile should not be considered a central estimate. • For fluvial floods, the choice of scenario and probability should be appropriate to the purpose of the study for instance, a modelling study to inform the design of a flood defence around a site of critical national infrastructure may wish to use a more conservative climate change allowance. The scenario or scenarios used should be justified in the modelling report and ideally a sensitivity analysis to different allowances should be carried out.
Flood protection appraisals: guidance for SEPA and responsible authorities, (The Scottish Government, 2016)	• All significant flood risk (economic, social and environmental) should be identified including the effects of climate change. [3.1.3] • The objectives should be aspirational and not set limits on what is possible/ desirable. For example, it is not acceptable to state that the purpose is "to develop flood embankment with a 1% annual exceedance probability (AEP) (1 in 100 year return period) design standard". [3.2.2] • Consideration must be given to a broad range of structural and non-structural actions. [4.2.1] • Standard lists of actions that can be used as a starting point are published by SEPA (2015b; In prep.). [4.2.2] • Consider the impact that actions will have on flood risk now and in the future. Actions to manage flood risk should reflect the needs of future generations and be adaptable to a changing climate and other drivers of changing flood risk. (Sections 4.6, 5 and 9.8). [4.2.7] • A high level scoring or matrix analysis exercise may be helpful. [4.3.4]

	• Ministerial guidance (Scottish Government 2011a) does not specify certain design standards – but it does expect all appraisals to include an option that protects to a 1% AEP plus allowances for climate change. Other incremental levels of protection should to be considered during option development. [4.6.3] • Because of the uncertainties in projections of future flood risk, it is preferable wherever possible to design actions that can be adapted in future (a managed adaptive approach) rather than to design for climate change and other changes up front (a precautionary approach) (Box 4.2). However, this may not be possible for large one-off interventions where building in climate change and other future adaptations at the start may be the only feasible approach. [4.6.5] • The following components should be assessed: Adaptability to climate change and other drivers of future flood risk. [5.1.2] • The flood risk impacts and wider impacts should be described, and if appropriate/possible, assessed in quantitative or monetary terms. There are advantages to estimating the impacts in monetary terms: these impacts can be readily compared with whole life costs to estimate the likely return on investment by calculating net present values (NPVs) and benefit-cost ratios. (BCRs) [5.2.1] • There are a range of techniques that can be used to appraise and help select the preferred option. The technique chosen will depend on the complexity of the problem being addressed. [5.2.3] • Appraisal techniques such as cost-benefit analysis (CBA) and multi- criteria analysis (MCA) provide metrics for comparing options. [5.2.5] • The discount rates recommended by the HM Treasury Green Book (2011) should be used for all streams of benefits and costs. [5.3.2] • The presumption is that for most appraisals, a 100-year timeframe will be appropriate to enable comparison of option. Longer timeframes also better allow for environmental or adaptation benefits to be included in appraisals. [5.4.5] • Data collection and modelling can be one of the most expensive parts of a cost-benefit analysis. Appraisals should seek to build on existing modelling work, for example, SEPA's strategic flood hazard and risk modelling. [5.5.5] • The appraisal process should seek to fully understand risk in a changing climate and should be in accordance with the Scottish Government's guidance on Public Bodies Climate Change Duties (2011c) and the objective of the Scottish Climate Change Adaptation Programme (Scottish Government 2014b). [9.8.3] • The likely effects of the changing climate should be consistently taken into account in appraisals using up-to-date evidence. There is, however, a relatively large degree of uncertainty in climate predictions that makes it difficult to accurately model and assess risk. It is therefore important that uncertainty is understood, managed and accounted for in the

	determination of the future scenario(s); so, awareness and use of a probabilistic approach to future assessment of risk might be applied. [9.8.4] • A proportionate approach should therefore be taken when considering future climate change: where the receptor vulnerability is likely to be high, a more extreme (precautionary) scenario might be considered (e.g. a High emissions scenario) and a more conservative predictive curve used to consider future change in peak flow. [9.8.6] • Possible approaches for taking climate change into account in appraisal are described below. [9.8.7] ◊ a) Use existing flood models. ◊ b) Model changes in hazard and risk, it is possible to calculate a number of different annual average damages corresponding to the different conditions (e.g. 2050s, 2080s). These estimated benefits can be used in the following ways, depending on the type of study: ○ Annual average damages can be calculated for appropriate years, and values interpolated for intervening periods. Benefit-cost ratios can be estimated both with and without climate change. ○ A near-future climate change scenario can be factored in the appraisal from the start (as confidence in near-future climate change scenarios is greater than for more distant scenarios). • c) Sensitivity analysis. For high level strategic studies, sensitivity analyses (Section 11.7) may provide a proportionate approach to initially consider the future impacts of climate change. The analysis should make best use of available data acknowledging the associated limitations and uncertainties.
Natural flood management handbook, (SEPA, 2015a)	• Sets out guidance for monitoring Natural Flood Management projects, including monitoring of hydrology, hydro-morphology and ecology.
Scottish Climate Change Adaptation Programme (SCCAP)[3]	• Due to the inherent uncertainty in some aspects of climate change, adaptation policies need to be flexible and adjusted as and when new information becomes available. • In some areas immediate, practical action is needed now whereas for others flexible, long-term strategic planning is required.
Surface water management planning: guidance (The Scottish Government, 2018)	• Makes reference to three influences on future flood risk: climate change, urban creep, demographic change. • Points to guidance on considering adaptation in option appraisals. • “When designing options, allowance should be made for climate change. What allowance to include will vary, depending, for example, on the type or location of the option

[3] At time of writing, an update to this document was under consultation

	and whether a managed adaptive or precautionary approach is being taken". • Consider actions that can be implemented in the short term, as well as longer term, aspirational ones. • Climate change in particular poses serious challenges and risks for managing flooding in Scotland. Its impacts include the potential rise in intensity and frequency of rainfall events increasing the risk of surface water flooding. • Provides guidance on assessing the impact of options on climate change adaptability. Two adaptation approaches are described in the Defra 2009 policy statement. Both approaches could also be applied to urban creep and population growth. For each option, an indication of which approach is likely to be implemented should be given: iv. Managed adaptive – this approach allows for adaptation in the future by planning multiple 'phased' interventions over time. The first phases can initially use lower allowances for climate change over the shorter term, with further interventions implemented if and when required. Change in risk is monitored over the lifetime of the actions and any change managed through multiple 'phased' interventions (often interventions are implemented after a trigger point, indicating that the risk will become unacceptable, is reached). This approach is flexible enough to manage future uncertainties associated with climate change during the whole life of a flood risk management system. Other benefits of managed adaptive approaches are: ○ They can be less costly – as future adaptation phases have been planned from the start and can be implemented if and when required, the need to introduce new or significantly change existing actions to manage future changes may be avoided. ○ They use a risk-based decision framework – enabling risk to be monitored and managed at periodic intervals during the design life of a development. ○ They are usually more sustainable over the long term – presenting opportunities for enhancing the environmental, societal benefits and cost savings that cannot be achieved through precautionary approaches. ○ They can take advantage of innovative advances over time and are sufficiently flexible to cope with changing climate change projections that may differ from those available to us today. v. Precautionary – in some circumstances, future adaptation may be technically unfeasible or too complex to administer over the long term. Hence this approach, resulting primarily in one-off interventions with a higher allowance in the design for climate change over the longer term, may be the only feasible option (such as in the design capacity of a major culvert or underground storage).

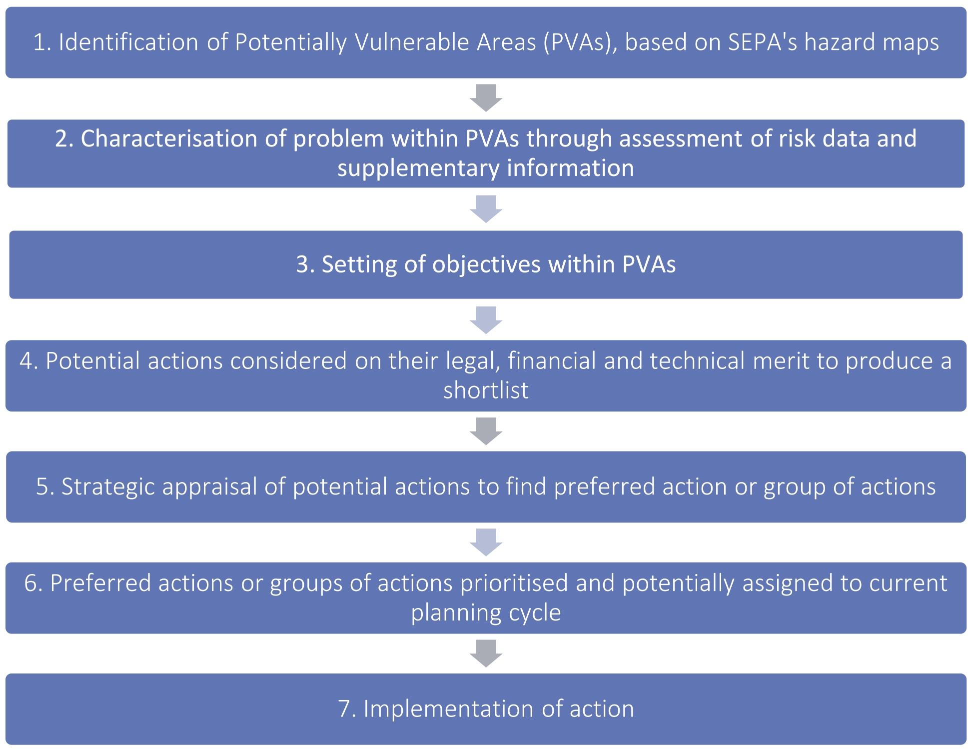
	• For each option a short description of the level of intervention, the costs and feasibility associated with ensuring that the action can respond to changing conditions should be provided. The assessment may include: ◊ A description of likely impacts of climate change and other drivers. ◊ A description of adaptability to climate change – e.g. whether a managed adaptive or precautionary approach is being taken and how it will be implemented. ◊ A description of adaptability to other future flood risks – urban creep and demographic change (managed adaptive or precautionary approaches may also be used for these factors). ◊ Information on the level of intervention, costs and feasibility associated with ensuring that the option can respond to changing flood conditions. ◊ It may be helpful to present this information as a class or score in an appraisal summary table.

Source: Various

Appendix 2: Flood Risk Management process

Scotland's approach to Flood Risk Management is set out in the 2009 Flood Risk Management Act. In each six-year cycle flood risk is identified, potential actions to mitigate risk are generated, appraised, selected and then implemented. The Act places duties on the Scottish Environment Protection Agency (SEPA), local authorities, Scottish Water and other 'responsible authorities'.

Figure 10. Stages in the strategic decision-making process



Source: Vivid Economics

A National Flood Risk Assessment takes place every six years. Using flood hazard maps produced by SEPA which cover both present-day and future flood risk from pluvial, fluvial and coastal flood, the assessment reviews flood risk to a wide variety of receptors to identify Potentially Vulnerable Areas across Scotland. These are areas where significant flood risks exist presently or are expected to occur in the future. Works within Potential Vulnerable Areas (PVAs) are eligible for Scottish Government grant funding. Climate change information is used in the selection of Potentially Vulnerable Areas and for the creation of the flood hazard maps, as shown in Table 6. These are based on single climate change scenarios.

Table 6 Use of climate change information in flood hazard maps

Source	Use of climate change information
Fluvial	200 year plus climate change allowance extent map, based on UKCP09 2080s high emissions scenario, 67th percentile
Pluvial	200 year plus climate change allowance extent map, based on a 20% increase in rainfall nationally.

Coastal	200 year plus climate change allowance extent map, based on UKCP09, high emissions, 95th percentile

Source: Vivid Economics based on SEPA

Within each planning cycle, 14 Flood Risk Management Strategies identify actions to manage flood risk in each of the Potentially Vulnerable Areas. Actions might include flood protection studies, flood protection schemes/works, or strategic mapping/modelling, amongst many others. Actions are assessed and selected based on their economic, social and environmental criteria. Flood Risk Management Strategies (and later Local Plans) are developed in partnership between SEPA and responsible authorities and are subject to consultation.

Local Flood Risk Management Plans identify how selected actions will be implemented at the local level. For actions selected in the prioritisation process, the plans identify who will be responsible for their delivery, when the actions will be undertaken and how the actions will be funded. Where a flood protection study is to be carried out, this will involve a full economic appraisal and calculation of benefit-cost ratios of potential measures. Typically, responsible authorities will engage engineering consultancies to carry out economic appraisal in accordance with published guidelines.

Based on the economic appraisals, SEPA selects a subset of the actions and assigns them to the planning cycle in a process known as prioritisation. The prioritisation exercise is based on a combination of the evidence of proposed costs and benefits and the local needs expressed through the local partnerships. Through this process, 42 formal flood protection schemes were prioritised in the planning period between 2016 and 2021(SEPA, 2015). The prioritisation process in Cycle 2 is under development but will be based on a broadermulti-criteria analysis.

Appendix 3: Climate change uplift values

Table 7 Uplift values recommended by SEPA for surface water studies

Location	Water & sewerage company applicability	Duration (hours)	Epoch								
			2030s			2050s			2080s		
			L	C	H	L	C	H	L	C	H
NW (Glasgow)	Scottish Water (west)	1	14	19	25	16	27	37	23	50	88
		3	0	7	10	0	6	11	11	22	29
		6	8	12	18	0	7	20	4	20	36
NE (Newcastle)	Scottish Water (east)	1	20	28	40	24	44	75	45	50	60
		3	12	15	16	18	29	41	35	53	76
		6	5	7	10	8	17	30	33	51	75

Notes: L = Low, C = Central, H = High
Source: UKWIR

Table 8 Percentage change in flood peak

			% change in flood peak (threshold based on exceeded likelihood)									
Scenario	Probability (%)	Exceedance likelihood	Orkney/ Shetland	N Highland	W Highland	NE Scotland	Argyll	Tay	Clyde	Forth	Solway	Tweed
Low	10	very likely to be exceeded	15	7	12	2	12	4	8	5	6	5
	33	likely to be exceeded	20	14	23	10	23	12	16	13	13	11
	50	is as likely as not to be exceeded	27	18	30	13	30	16	20	17	18	14
	67	unlikely to be exceeded	30	24	36	16	36	20	26	22	23	19
	90	very unlikely to be exceeded	38	33	50	24	50	31	35	32	35	28
Medium	10	very likely to be exceeded	16	10	15	3	15	7	11	7	8	6
	33	likely to be exceeded	27	18	29	11	29	15	20	16	16	13

	50	is as likely as not to be exceeded	30	23	36	14	37	20	27	21	22	17
	67	unlikely to be exceeded	34	29	44	18	45	25	32	27	28	22
	90	very unlikely to be exceeded	45	40	60	28	60	37	45	40	45	32
High	10	very likely to be exceeded	18	12	20	4	20	11	15	11	13	9
	33	likely to be exceeded	29	23	36	12	36	20	27	22	25	18
	50	is as likely as not to be exceeded	33	29	45	17	45	26	34	28	32	23
	67	unlikely to be exceeded	41	37	56	24	56	35	44	40	44	33
	90	very unlikely to be exceeded	53	50	>60	33	>60	50	60	54	60	45

Notes: Percentage uplifts of the high, medium and low emissions scenarios for the 2080s, from Kay et al., 2014

Table 9 Example information basis for sea level change estimates

	2020			2050			2095		
	5th	**50th**	**95th**	**5th**	**50th**	**95th**	**5th**	**50th**	**95th**
Low	0.6	4.3	8.0	1.9	10.5	19.1	5.2	23.4	41.6
Medium	0.9	5.7	10.6	2.6	13.9	25.2	6.7	30.5	54.3
High	1.3	7.5	13.7	3.6	18.0	32.3	9.0	39.2	69.5

Source: Duck et al., 2012

Appendix 4: Examples of structural and non-structural adaptive options

Table 10

Structural	Non-structural
Some hard defences may need to be sustained in the short term to 'buy the time' required to prepare communities for policies which may lead to a required change in land use. For example, there could be the case for continuing to maintain and repair defences for 5 to 10 years while preparing communities for and developing policies of managed realignment or active intervention.	Develop and deliver a tiered, enhanced support package for communities to adapt to coastal change informed by existing successful adaptation measures, broader plans (e.g. Shoreline Management Plan) and coastal change adaptation strategies (e.g. community strategy, local plan core strategy).
Building the potential for future adaptation into new flood defences (e.g. building foundations that are larger than required for the current height of the defence enabling heightening in the future if required).	Development of local partnerships to develop options and plans for change, including studies to gather historical, economic, visitor and landscape information to inform consideration of options.
Even where structures are built, it may be possible to include a degree of adaptation by limiting the standard of protection and/or the design life. For example, a lower quality structural solution might involve placing a limited amount of rock armouring at the base of an eroding cliff to reduce, but not prevent, its recession. In flood risk areas, similar approaches might involve designing an earth embankment with a limited standard of protection. Such solutions could be used to allow a local community more time to adapt and find a long-term solution.	Information measures (e.g. warning, awareness raising etc.) are all important, help improve preparedness and resilience and reduce vulnerability. Community-level adaptation supported by the move towards localism.
Another example could be use of rock in preference to concrete for beach management groynes or erosion protection revetments where the uncertainties are unresolved. The rock can be reused at a different location depending on how the shoreline processes evolve.	Community-focused schemes will help raise awareness, thus increasing preparedness, and ensure that community-based operations are implemented etc.
	Deliver practical support to facilitate relocation for those at risk – for example, through discussions with utilities and other service providers and identification of possible sites for relocation. Increase awareness of erosion/flooding processes by, for example, installing a viewing platform so that local people can see coastal erosion processes in action.

Source: Environment Agency, 2018

Appendix 5: Glossary

Table 11 Glossary

Term	Definition
Action	Describes where and how flood risk will be managed.
Annual average damages (AAD)	Annual Average Damages are the theoretical average economic damages caused by flooding when considered over a very long period of time.
Annual exceedance probability (AEP)	Probability that a flood event of specified magnitude will be equalled or exceeded in any year (also see "return period").
Appraisal	Appraisal is the process of defining objectives, examining options and weighing up the costs, benefits, risks and uncertainties before a decision is made.
Benefits	Positive quantifiable and unquantifiable changes that an action will produce.
Benefit-cost ratio (BCR)	Summarises the overall value for money of an action or project. It is expressed as the ratio of the benefits to costs (both expressed as present value monetary values). If the ratio is greater than one then the project is deemed to be economically viable. A ratio of greater than 1:1 indicates that the economic benefits associated with an action are greater than the economic costs of implementation; therefore this is taken as the threshold of economic viability.
Discounting	The procedure used to arrive at the sum of either costs or benefits over the lifetime of an action using a discount rate to scale down future benefits and costs. The effect of using a discount rate is to reduce the value of projected future costs or benefits to their values as seen from the present day.
Dynamic Adaptive Policy Pathway	A plan which is monitored for signals ("triggers") and once these are reached, contingent actions are taken.
FCERM	Flooding and Coastal Erosion Risk Management Network
Flood extent	The area that has been affected by flooding or is at risk of flooding from one or more sources.
Flood hazard	In terms of the Flood Risk Management (Scotland) Act 2009, hazard refers to the characteristics (extent, depth, velocity) of a flood.
Flood hazard map	Flood hazard maps are required by the FRM Act to show information that describes the nature of a flood in terms of the source, extent, water level or depth and, where appropriate, velocity of water. Flood hazard and risk maps are referred to collectively as flood maps and are available on the SEPA website.

Flood risk	A measure of the combination of the likelihood of flooding occurring and the associated impacts on people, the economy and the environment.
Full appraisal	An appraisal that prioritises the investment strategy that maximizes expected net benefits, accounting for anticipated learning about climate change and trade-off between costs and flexibility.
Natural flood management (NFM)	A set of flood management techniques that aim to work with natural processes (or nature) to manage flood risk.
Net present value (NPV)	The stream of all benefits net of all costs for each year of the option's life discounted back to the present date.
Option	An option is a combination of one or more flood risk management actions, developed to meet an objective.
Present value	The value of a stream of benefits or costs when discounted back to the present time.
Real options analysis	An approach to decision making that recognises uncertainty and examines how decisions made today influence ability to respond to that uncertainty in the future.
Receptor	Refers to the entity that may be impacted by flooding (a person, property, infrastructure or habitat). The vulnerability of a receptor can be modified by increasing its resilience to flooding.
Return period	A measure of the rarity of a flood event. It is the statistical average length of time separating flood events of a similar size: a 100-year flood will occur on average once in every 100 years. The longer the return period, the rarer the event. (Also see “Annual exceedance probability”).
Sensitivity analysis	Analysis of the effects on an appraisal of varying the projected values of important variables.
Single future appraisal	An appraisal that prioritises the investment option which maximizes net benefits under a particular climate change scenario.
Standard of protection (SoP)	The flood event return period above which significant damage and possible failure of the flood defences could occur.
Sunk costs	A cost incurred in the past and which cannot be recovered whatever decision is taken now. Consequently, sunk costs are omitted in cost-benefit analyses.
Sustainable flood risk management	The sustainable flood risk management approach aims to meet human needs, whilst preserving the environment so that these needs can be met not only in the present, but also for future generations. The delivery of sustainable development is generally recognised to reconcile three pillars of sustainability – environmental, social and economic.

Tipping point	The point at which a flood risk prevent measure no longer meets its objective
Trigger point	The point at which a decision maker might need to take adaptation options to maintain required standard of protection. Trigger points precede tipping points of measures due to the consideration of lead times.

Source: Vivid Economics, SEPA (2015)

Appendix 6: International case studies

Levee Reinforcement program, The Netherlands

Overview

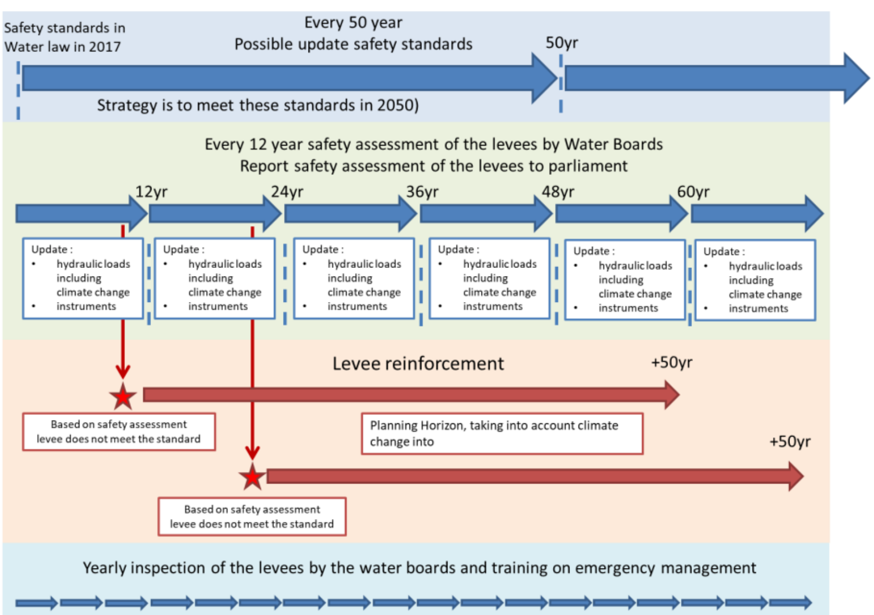
This program makes use of adaptive pathways based on multiple scenarios to manage increasing flood risk and sea-level rise at the national scale. This levee reinforcement program follows a dynamic process designed to respond to new climate change information. Every 12 years, the strength of the primary levee systems is reevaluated. The evaluation includes a check as to whether climate conditions have changed. The levees are evaluated using the legal norms for primary levees to check whether they satisfy.

The level of tolerable risk is established every 50 years using a risk-based approach taking account of expected risk and future costs (Jonkman et al, 2018). If the levees do not meet the standard during the evaluation, the levee is prioritized for reinforcement.

The regional water authority is responsible for the process of levee reinforcement. A decision is made on how to reinforce the levee; this involves a choice of life cycle as well as the selection of 4 regionalized climate scenarios (which are updated according to latest IPCC findings). In a 3-step trajectory the reinforcement is implemented:

- Phase 1: Exploration: Together with the stakeholder in the region, different options for reinforcement are explored. Levees are adaptable solutions and can be integrated in strategies which combine the development of the landscape, urban development and levee reinforcement. Social Cost-Benefit-Analysis is performed in which the impact on the environment is included.
- Phase 2: Design
- Phase 3: Implementation. The reinforcement budget is split equally between the national government and the water boards.

Figure 11.



Source:

Relevance to the Scottish decision-making process

- The program makes use of climate scenarios and reassesses risk based on new climate change information every 12 years.
- The economic appraisal method assesses the likelihood of various climatic and economic scenarios. The safety standards for the levees depend on the tolerable risk which changes due to economic developments.
- As the process includes a social cost-benefit analysis performed by the local water authority and regional stakeholders, the reinforcement program is an opportunity to create added ecological, social value in flood risk management solutions.

Delta Plan on Spatial Adaptation, The Netherlands

Overview

The Delta Plan on Spatial Adaptation is a collective plan set up by municipalities, district water boards, provinces, and the national government to improve the Netherlands' resilience to climate change. The plan consists of (1) mapping out vulnerabilities (Analysis), (2) subsequently formulating goals (Ambition), and realizing measures to create climate-proof and water-resilient municipalities (Action).

Municipalities and district water boards are obliged to perform a climate stress test for their region before 2020. The stress test examines the impact of heat, drought, extreme rainfall, and flooding in the region in 2050. The hazard mapping involves a selection and choice of climate scenario, with guidelines provided as how to perform a stress test and how to interpret and apply the results. Often municipalities are supported in hazard mapping by a consultant.

Relevance to the Scottish decision-making process

Once the results of the stress test are available and the consequences of extreme events are mapped and visualized, the municipalities, district water boards, provinces, and the ministry of infrastructure and water management will launch a dialogue with all the relevant partners in each region or sub-region. This stakeholder engagement process has been labelled the 'risk dialogue'. As part of this, stakeholders in the area discuss the exposure of people and infrastructure to climate effects, define the acceptable level of risk and explore possible solutions.

Multi-layered safety, Venlo, The Netherlands

Overview

The multi-layered safety (MLS) approach focuses on flood risk reduction through three types of measures: (1) prevention through dykes, levees and dams (2) a flood resilient spatial planning and (3) adequate crisis management (Leskens et al, 2013). Multilayered Safety (MLS) intends to integrate different types of measures into Dutch flood management to reduce both the probability and the consequences of floods. Before the introduction of the MLS approach, the Netherlands has mainly relied on flood prevention, thus probability-reducing measures.

MLS consist of three layers. The first layer focusses on protection and prevention. The second and third layers are consequence-reducing measures, namely spatial solutions and crisis management. The first two layers are physical measures, whereas crisis management concentrates on organizational measures (Hoss et al., 2011).

The MLS project in city of Venlo along the river Meuse, an example of a combination of levee reinforcements, urban development and emergency management, are evaluated. Different strategies for 2030 and 2050 have been developed which consider four climate scenarios. Often the worst case climate scenario is opted for in order to gain a robust future position.

A wide set of options is defined, from which a number of options are selected. A multi criteria analysis is used to evaluate these measures. Criteria are 'hard' criteria quantified in monetary terms (costs, risk) and soft criteria (on a scale of 0-5) of parameters which are more difficult to monetarize. Economic appraisal is performed using a participatory and multi-criteria approach to make local-level decisions on the actual design of flood control infrastructures.

Relevance to the Scottish decision-making process

- Shows how to integrate long-term spatial planning developments in flood risk management.
- Flood risk management interventions (prevention) in the water management systems have a direct effect on the surrounding areas, which raises opportunities to develop other spatial functions.
- A multi-criteria analysis is used in optioneering/shortlisting a combination of measures, which helps ensure that adaptive options do not get prematurely screened-out during the optioneering/short-listing process.

Island of Hokkaido, Japan

Overview

Hokkaido, the second largest island of Japan, suffered from typhoons in August 2016, which caused huge damages to the whole of Hokkaido. The exceptional heavy rain and large-scale inundation due to breaching of the dyke caused damage to main roads, bridges and railways, houses, people and large agricultural areas. A committee was established to examine how to prevent future flood disaster, by examining climate projections, water management planning, and disaster risk management.

Relevance for Scottish decision-making process

The committee established a basic policy to consider flood risk broadly and investigate the increased flood impact of a range of climate scenarios. The flood risk (scale, form and frequency) caused by climate change is based on the latest knowledge of climate change. The IPPC scenarios are translated to a local projection for future rainfall for Hokkaido area. Simulated flood discharges are compared against historical discharge data. The wetted surface area in the catchment serves as an input to the LIFE-SIM risk model, which calculates the number of flooded houses and estimates loss of life for under each climate scenario.

Coastal adaptation, New Zealand

Overview

Local Government New Zealand highlights sea-level rise as one of the key factors that will greatly affect coastal communities. To cope with the variability of climate change effects and the range of uncertainties in coastal areas that ongoing sea-level rise poses for decision-makers, adaptive pathways planning is now embedded as an assessment tool in draft revised national coastal hazards guidance for local government. The integration of adaptive pathways in the national guidance was facilitated through use of simulation games tested in three local governments, Greater Wellington Regional Council, Tasman and Nelson district, to catalyze its uptake and test its relevance in real life for flood risk management decision-making processes (Lawrence & Haasnoot, 2017).

Relevance for Scottish decision-making process

Adaptation Pathways Planning enables active community and stakeholder engagement and community capacity building to ensure that all stakeholders understand the value of adaptive solutions. The primary function of establishing a collaborative process to explore values and objectives is to develop a joint understanding of the problem, what is important and to whom, so objectives can be developed to guide the adaptive decision-making process.

Pathways are a series of actions over time to achieve the agreed objectives under uncertain and changing conditions. By exploring different pathways and testing the consequences under the different scenarios, an adaptive plan can be designed that includes a mix of short-term actions and long-term options. When screening and shortlisting different options, the value of flexibility and adaptiveness are weighed as part of a multi-decision analysis criteria.

To monitor the pathway strategy as conditions change over time, there needs to be a way to measure when an option or pathway no longer meets its objectives and needs to be adjusted. Trigger points are developed in response to the rising sea level. Sea level rise is monitored and when/if it reaches the pre-determined trigger points further actions are taken.

Appendix 7: Scottish case studies

Stonehaven Bay

Overview

Stonehaven is a coastal town about 20 kilometres south of Aberdeen, with a population of around 11,000. Stonehaven and the village of Cowie lie within Stonehaven Bay, into which the rivers Carron and Cowie discharge. Stonehaven was identified as being at risk of flooding from pluvial, fluvial and coastal sources in the North East Local Flood Risk Management Plan (LFRMP). The LFRMP estimates coastal flooding as generating £30,100 of Annual Average Damages. There is a history of flood events in Stonehaven, with an event in 2012 resulting in structural damage and risk to life. A map of the area is shown in Figure 1.

JBA Consulting was commissioned by Aberdeenshire Council to undertake a coastal Flood Protection Study to consider options to reduce coastal flood risk within Stonehaven and Cowie. An information review report, supplementary studies, interim modelling report and initial economic appraisal have been completed. Outcomes of the economic appraisal were presented to the public in June 2019. A preferred option will be identified and submitted to SEPA for prioritisation for funding in 2021 to 2026. Information on the Stonehaven Bay Flood Study is available at [http://www.stonehavenbaycoastalfloodstudy.com.](http://www.stonehavenbaycoastalfloodstudy.com)

Figure 12. Map of Stonehaven

Note: Contains Ordnance Survey data, Crown copyright and database right 2018

Source: JBA

Present day risks

The assessment of coastal flood risk divides Stonehaven Bay into three 'Benefit Zones': the zones are labelled North, Central and Harbour. For the purposes of economic assessment, the flood risk of the zones are assumed to be independent, enabling separate appraisal for each Benefit Zone.

Under baseline conditions, the model estimates Present Value of Damages across all Benefit Zones of approximately £25 million over the 100 year appraisal period. Wave overtopping is the primary mechanism that results in coastal inundation. Flood risk due to still water levels (SWL) alone is limited within Stonehaven and Cowie. A flooding event in 2012 resulted in structural damage and risk to life, and has been used to calibrate JBA's model.

Flood risk has been assessed using a suite of numerical models to simulate all the elements of coastal flood risk and incorporate uncertainty. There is no one modelling package available that can simulate all elements of coastal flood risk simultaneously. As a result, the following models were combined:

- Dependence models describing the relationships between offshore waves, wind and still water levels based on a subset derived from a full multivariate statistical data set using a maximum difference algorithm (MDA);
- Still water level elevations for a range of return periods from the 2018 Coastal Flood Boundary Dataset;
- A cut-down of SEPA's existing SWAN model to transform offshore waves to the nearshore, calibrated to the Stonehaven wave buoy;
- Emulators at the toe of each defence to provide nearshore conditions for the full multivariate dataset;
- Wave overtopping schematisations using neural networks that were calibrated for historical events;
- A detailed flood inundation model forced by an offshore tidal graph in conjunction with overtopping inflows so as to produce a single flood extent that represents the risk from both mechanisms. Inundation is represented as a composite risk from both still water levels and wave overtopping.

Future risks

Modelled damages from flood risk triple under 95th percentile sea level rise in the UKCP18 medium emissions scenario. Climate change is expected to result in recreational losses through erosion of the beach, cause risk to life from wave overtopping, and put critical infrastructure at risk from erosion and sea level rise (JBA Consulting & Aberdeenshire Council, 2019). Sea level rise due to climate change has the potential to significantly affect additional parts of the drainage network. Table 12 shows the increase in Annual Average Damages (AAD) for each Benefit Zone between 2018 and 2118 under the considered climate change scenario.

Table 12 Changing risk levels between now and 2118

Benefit Zone	2018 AAD (£k)	2118 AAD (£k)	Total PvD (£k)

North	50	93	1,836
Central	223	927	12,595
Harbour	225	798	11,360
All	508	1,817	25,791

Note: Extreme sea levels have been uplifted to 2118 levels, giving an increase of 0.73m from present day (2018) conditions. AAD = Annual Average Damages, PvD = Present Value of Damages
Source: JBA

Uncertainty in wave overtopping estimates contributes to uncertainty in the modelling results. Although the flood study attempted to solve this by using neural network schematisations, there is still uncertainty stemming from modelling waves within the harbour, which contributes to flood risk uncertainty.

There is a large degree of uncertainty around the response of beach erosion to flood events. The attempts to conduct long-term simulations have been limited both by computational effort and the accumulation of errors through time. As the coastal defences are critical to preventing the exposure and damage of key infrastructure, this leads to a large degree of uncertainty of potential damages (JBA Consulting & Aberdeenshire Council, 2019).

Value of adaptive planning

The appraisals document tests the value of adaptive planning in Stonehaven by estimating the Benefit Cost Ratio of flood risk management measures under three approaches:

- **Precautionary**: Replace current defences with defences that incorporate a climate change allowance
- **Adaptive**: replace current defences now and adapt to climate change over the appraisal period
- **Delayed**: keep current defences until failure and then replacing with defences that incorporate a climate change allowance

The appraisal begins with the identification of a short-list of measures for each benefit zone. In most cases, two variants of each measure are considered: one providing a 1 in 200-year Standard of Protection (SoP), the other providing a 1 in 200-year plus climate change SoP (median emissions scenario, 95th percentile), with the intention that the 1 in 200-year SoP measure could be adapted to 1 in 200 year plus climate change. Across all benefit zones, measures considered include new sea wall defences, rock revetment and beach recharge schemes. Options for the Central Benefit Zone are show in Table 13.

Table 13 Considered measures for the Central Benefit Zone

Option	SoP	Timescale
Walls along river Cowie	200-year + CC	Long
Sea Wall 1	200-year	Medium

Sea Wall 2	200-year + CC	Long
Beach Recharge 1	200-year	Medium
Beach Recharge 2	200-year + CC	Long

Note: There is no benefit in adaptive approach on the Cowie, since the difference in present day and climate change designs are small
Source: JBA

Individual measures are then combined into a series of potential pathways for each benefit zone, and economically appraised using standard methods. These pathways include the adaptation of measures in response to climate change. Potential pathways for the Central benefit zone are displayed in Table 14. For the purposes of appraisal, Annual Average Damages (AAD) were calculated for 2018 and 2118 and interpolated linearly for years in between. Delayed and adaptive costs are assumed to occur in year 30, corresponding to the residual life of most existing defences. No explicit allowance was made for possible changes in information about flood risk.

Table 14 Pathways for Central Benefit Zone

Option	Name	Start	Mid	End	Approach
1	Do minimum				
2	Cowie Walls plus adaptive sea walls	Sea wall 1 and Cowie Walls	Sea wall 2 and Cowie Walls	Sea wall 2 and Cowie Walls	Adaptive
3	Cowie Walls plus adaptive recharge	Recharge 1 and Cowie Walls	Recharge 2 and Cowie Walls	Recharge 2 and Cowie Walls	Adaptive
4	Cowie Walls plus precautionary sea walls	Sea wall 2 and Cowie Walls	Sea wall 2 and Cowie Walls	Sea wall 2 and Cowie Walls	Precautionary
5	Recharge medium	Recharge 1	NA	NA	Upfront

Note: Combinations with BCRs greater than unity are highlighted in green
Source:

Results from appraisals of the pathways in each benefit zone show:

- **For the North Benefit Zone, any option that involves building a new structure in year 0 is economically unviable.** Delayed investment options can provide a BCR above 1, and are more cost effective than adapting the measures in response to climate change.
- **For the Central Benefit Zone, only an adaptive pathway is economically viable.** In this pathway, a new recharge scheme is built at the present day and adapted in response to

climate change and new walls are built along the River Cowie in year 30. Again, all options which involve building a new structure in year 0 are economically unviable. For the sea wall it is shown that there is no significant economic benefit in building in year 0 and adapting the design over the appraisal period.

- **For the Harbour Benefit Zone, no new structural options provide a BCR above 1**, regardless of whether investment is delayed or not. A medium-term option of only considering Property Flood Resilience (PFR) for 30 years has a BCR above 1 and demonstrates the case for immediate investment in some form. Despite having a BCR less than 1, two other structural options were taken forward, ensuring that medium- and long-term options are available for assessment in the next stage.

Upon analysis of the individual Benefit Zone results, economically viable options for each zone were taken forward to assess as options across the entire bay. All combinations are economically viable, achieving BCR>1**.** Table 15 provides a summary of the combined options and the results from the appraisal.

Table 15 All combinations are shown to be economically viable

Combination of pathways
North 7: Wall raise and new wall in year 30 **Central 4**: Adaptive recharge **Harbour 7**: Property flood resilience and new rock revetment (north), stepped revetment (inner) and managed realignment (south) in year 30
North 8: Wall raise and new rock revetment in year 30 **Central 4**: Adaptive recharge **Harbour**: Property flood resilience and new rock revetment (north), stepped revetment (inner) and managed realignment (south) in year 30
North 9: Wall raise and new recharge in year 30 **Central 4**: Adaptive recharge **Harbour 7**: Property flood resilience and new rock revetment (north), stepped revetment (inner) and managed realignment (south) in year 30
North 7: Wall raise and new wall in year 30 **Central 4**: Adaptive recharge **Harbour 6**: Rock revetment (north) year 0; stepped revetment (inner) and managed realignment (south) in year 30
North 8: Wall raise and new rock revetment in year 30 **Central 4**: Adaptive recharge **Harbour 6**: Rock revetment (north) year 0; stepped revetment (inner) and managed realignment (south) in year 30

North 9: Wall raise and new recharge in year 30 **Central 4**: Adaptive recharge **Harbour 6**: Rock revetment (north) year 0; stepped revetment (inner) and managed realignment (south) in year 30
North 10: Wall raise **Central 5**: Recharge **Harbour 8**: Property flood resilience

Note: The economically viable options with a BCR>1 are highlighted in green.

The results of the options appraisal demonstrate that an adaptive approach to flood and erosion risk management is the most economically viable. For each benefit zone, the adaptive approach is as follows:

- **North**: Improve the existing defences immediately and adapt to a new option when the residual life is exceeded.
- **Central**: Implement an adaptive beach recharge scheme immediately and replace the defences around the River Cowie in year 30.
- **Harbour**: Manage the medium-term risk through PFR and construct new defences when the residual life of the current defences is exceeded (year 30).

Lessons from the case study

The case study shows that a simplified adaptive plan can be promoted through the current planning framework. A review of the materials presented and interviews with those involved in developing the plan highlights the following wider considerations.

Aspects of the appraisal that could be applied elsewhere:

- Making reference to multiple time periods and scenarios in Invitation to Tender (ITT) documents can spur the development of adaptive plans by consultants. In this case, the requirements set out by Aberdeenshire Council asked for options to be developed to manage risk in the “short”, “medium” and “long” terms, including both structural and non-structural elements. Consideration of a small number of time periods reduces appraisal complexity compared to modelling all years.
- Simplified approaches can be used to estimate damages at various points of time or at intermediate climatic outcomes. In this study, Annual Average Damages (AAD) were estimated using detailed modelling for 2018 and 2118 and damages for intermediate years were estimated through a process of linear interpolation. This approach significantly reduces modelling complexity compared to modelling each year.

Ways in which the appraisal might be expanded:

- A wider and more representative set of climate change scenarios would enrich the modelling by showing the true degree of uncertainty facing planners. The modelling is informed by a single climate change scenario, with hazards assessed at the 95th percentile. A wider set of scenarios, as well as the use of a more representative set of estimated impacts under each scenario, would more clearly highlight the range of uncertainty being faced. This richer set of climate scenarios might consider how certain damages might vary with the climate – for example, the value of the beach for tourism may increase in warming scenarios.

- An appraisal based on a fuller account of uncertainty could inform a truly adaptive plan including triggers and monitoring arrangements. Whereas the plan developed in the case study sets out a sequence of actions and timescales for interventions, a fully adaptive approach would make actions contingent on the revelation of future information risks. Such a plan would establish appropriate monitoring arrangements and trigger points for interventions.
- The exclusion of short term options from the modelling limits the extent to which the plans implement adaptive planning. Recommendations on appropriate short term options will be made to Aberdeen Council. These will include promotion of Property Level Protection, promotion of SEPA's Flood Warnings, repair and maintenance of existing defences and the monitoring and maintenance of beach levels. A fuller adaptive planning exercise would examine the protection offered by short-term interventions – and how this affects the case for longer term interventions as more information becomes available.

The case study also exemplifies general issues highlighted in Phase 1 of the work:

- **There is uncertainty as to how adaptive options will be received by the public.** In particular, consultants pointed to the need to take into account public perspective of future risk.
- The cost of conducting appraisal studies for adaptive approaches is significantly higher than for non-adaptive approaches and increases with the level of detail required. During the case study interview, the Council and the consultants stated that flood risk modelling in Stonehaven is particularly complicated, with considerable uncertainty involved in the different flood mechanisms and the expected change of their intensity over time. This limited the number of climate change scenarios that could be considered.

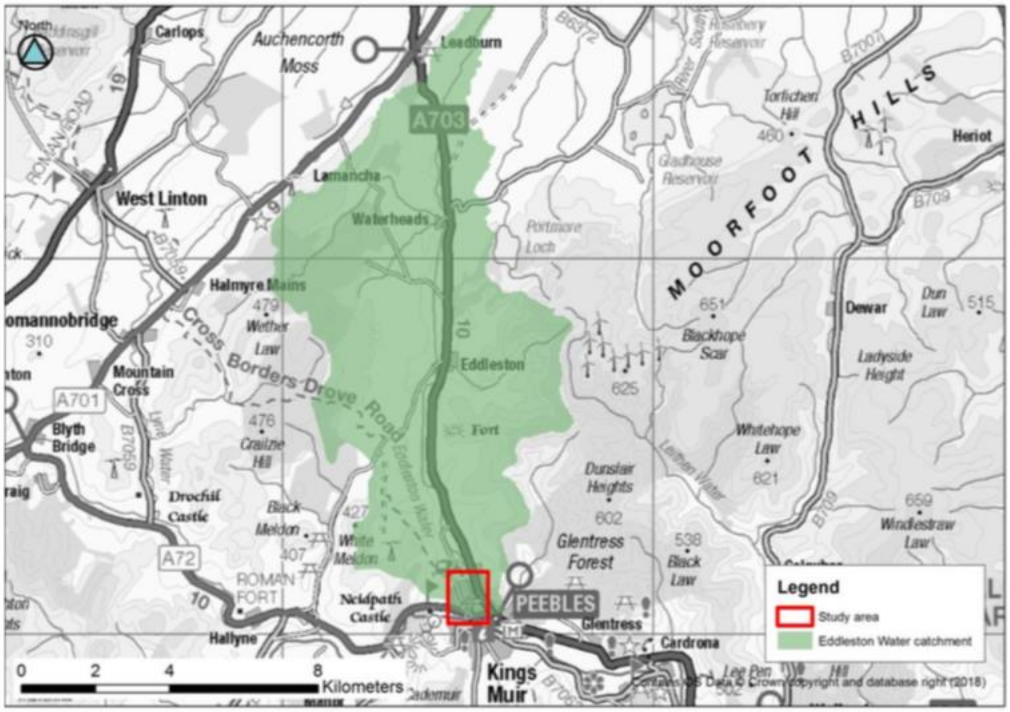
Eddleston Water and Peebles

Background

Eddleston Water is a tributary of the River Tweed in the Scottish Borders. It is typical of rural Scottish catchments of this size, with a mix of forestry, rough grazing and improved grassland. The catchment is 69km^2. The villages of Eddleston (population 335) and Peebles (population 8,376) are at risk of fluvial flooding from the Eddleston Water.

Peebles and the surrounding area was identified as a Potentially Vulnerable Area by SEPA during the first cycle of the Flood Risk Management Act. A flood study was commissioned by Scottish Borders Council and carried out by JBA consulting, with a final report produced in 2019.

Figure 13. Peebles and Eddleston Water catchment



Note: Contains Ordnance Survey data, Crown copyright and database right 2018
Source: JBA

The 'Eddleston Water project' was established in 2009 to investigate the effects of Natural Flood Management (NFM) on flood risk under present and future climate scenarios. The project is led by Tweed Forum and funded by the Scottish Government, Interreg and SEPA. Although the project is still ongoing, initial results have been made available and are used as the basis of the case study. Results from the Eddleston Water project have not been incorporated into the Peebles flood study, however they will be incorporated into the outline design and design phases of any scheme development.

Current risks

Flooding is a frequent and serious problem within Peebles, with risk from the River Tweed, Eddleston Water and surface water. There is a long history of flood events, with flooding to properties expected to begin at the 1 in 2 year flood under present conditions. Annual Average Damages from all sources in Peebles are estimated at £1.2 million under current conditions. Within Peebles, 73 residential properties and 9 non-residential properties are at risk of flooding from a 1 in 200 year event. There are currently no flood defence structures along the Eddleston Water.

Future risks

River flood flows are expected to rise with climate change. In this appraisal, a single climate change uplift in peak river flow of 33% by 2100 has been applied. Within Peebles, the number of residential properties at risk from a 1 in 200 year event rises to 120 under this uplift factor.

Value of adaptive planning

Building flood defences under a 'precautionary approach' to provide protection against extreme events in Peebles is not feasible. Even under present day conditions, the direct defences required to provide a 1 in 200 year Standard of Protection would have a large aesthetic affect within public spaces and the Council considers that this would not be accepted by the public. Defences would need to be even larger if climate change allowances were applied. As such, flood risk management plans have considered measures providing a lower Standard of Protection and shorter-term measures. The Peebles flood study investigates a range of measures, including Property Level Protection (providing a 1 in 5 years SoP), two direct defence options (each providing a 1 in 30 years SoP) and a direct defence option combined with raising of bridges (providing a 1 in 75 years SoP).

Considering Peebles in isolation, the appraisal found that there is currently no business case for smaller structural schemes. The direct defence option offering a 1 in 75 year SoP provides a BCR of 0.4. As a result, the flood study considers a number of non-structural and short term measures, including:

- Property Level Protection (PLP).
- Enhancing flood warning system and improving/increasing uptake in the community
- Updating emergency action plans
- Raising public awareness of flood risk
- Storage of community sandbags, including preparation of flood sacks filled with absorbent material which can be distributed before a flood
- **Property-level protection is found to be cost effective**. The option considered is to protect properties up to a flood depth of 0.6m. The options appraisal returns a BCR ratio of 1.3. However, since property-level protection provides only protection against shallow floods and the level of protection provided varies on a property by property basis, it does not provide a long-term flood risk management solution[4].

The phased abandonment of certain low-lying properties might be part of an optimal adaptive plan, since it is likely impossible to provide a high standard of protection to these properties. The report suggests that planning policy might be used to purchase properties as they become sold.

The Eddleston Water project shows that Natural Flood Management (NFM) actions can be effective as part of an adaptive response to flood risk (Dittrich et al, 2018). NFM measures can reduce flood risk by storing surface waters and delaying the peak floods, by increasing surface roughness and groundwater connectivity. Empirical results from Eddleston Water show that NFM might be beneficial as a flood management measure for smaller events and have a positive net present value under present conditions or lower/medium climate change scenarios climate change scenarios. This suggests that NFM measures should be combined with PLP or other measures. The full flood regulation benefits are only realised about 15 years after implementation: an adaptation response incorporating afforestation needs to take into account this lead time. When considering co-benefits of afforestation (e.g. carbon sequestration, habitat creation), afforestation has a net present value under all climate change scenarios.

A direct defences option providing a 1 in 75 year Standard of Protection becomes economically feasible when combined with a flood protection scheme on the River Tweed. Particularly at the downstream extent, flooding from the River Tweed and Eddleston Water are not wholly independent. A combined scheme is likely to be the most effective means of reducing flood risk in Peebles.

Vivid Economics has undertaken a high-level modelling exercise to test the potential value of adaptive planning in Eddleston and Peebles. Taking information from the appraisal study, this

[4] Scottish Borders offers a subsidy to owners of properties at flood risk. However, there has been limited uptake.

project has tested the value of adaptive vs non -adaptive approach. It was found that there is limited value in an adaptive plan combining measures contained in the appraisal study, since all measures have similar costs and none of the measures protect to a very high SoP. It was not possible to include NFM measures in the model, which have been shown to have a positive net present value on flood regulation under lower increases in peak river flow. The model is set up as follows:

- There are time periods: 2019-2039, 2040-2069, 2070-2119.
- At the beginning of each time period, the change in peak river flows can be high, medium or low, each with a probability 1/3rd. The magnitude of each potential change has been calibrated so that the distribution of potential peak river flows in each of the time periods matches the Tweed peak river flow allowances published by the Environment Agency in the "Flood Risk Assessment Climate Change Allowances" (Environment Agency, 2016).

Table 16 Increase in peak river flow

	Allowance for 2019-2039	Allowance for 2040-2069	Allowance for 2070-2119
Central (50th percenile)	20%	25%	45%
Higher central (70th percentile)	15%	20%	25%
Upper (90th percentile)	10%	15%	20%

Source: Environment Agency (2016)

- Annual Average Damages at any increase in peak river flow are estimated using the empirical relationship between peak river flows and Annual Average Damages, drawn from the appraisal study. This provides a means to estimate damages at any combination of climate change uplift.
- This project considers three possible adaptation measure above 'do minimum': Property-Level Protection, option 1 (direct defences with a present day 30-year SoP) and option 3 (direct defences with a present day 75-year SoP[5]). The size of flood event in terms of peak river flow that these options protect against are provided by the appraisal study: 27m^3/s, 40m^3/s and 60m^3/s respectively. Flood defences reduce Annual Average Damages by protecting against all events up to these magnitudes. Capital costs for installing the measures are drawn from the appraisal study and shown in Table 17 below.

Table 17 Costs and benefits of adaptation measures in Peebles

	PLP	Option 1	Option 3
PV costs £k	1,113	2,752	3,961

[5] For the sake of simplicity we exclude Option 2 in our analysis, as it has similar costs and benefits to Option 3.

PV benefits (avoided damage £k)	2,463	2,154	2,750

Note: Damage calculations under present day climate
Source:

- This project used a process of backwards induction to 'solve' the full decision tree at the beginning of each of the three periods, considering each possible realisation of climate change uncertainty and possible adaptation action. With similar costs and SoP between the various defence measures considered, an adaptive plan was not found to outperform a traditional approach: the model suggests it is not optimal to build at any time during the appraisal period. Given this, other measures which protect against smaller events (including NFM) can provide a valuable contribution to reducing flood risk.

Lessons from case study

The case study shows that NFM can be an important component of an adaptive plan. A review of the materials presented and interviews with those involved in conducting the appraisal highlights the following wider considerations.

Aspects of the appraisal that could be applied elsewhere:

- A paper resulting from the Eddleston Water project shows a simple method for designing optimal adaptive strategies and makes an example application of the methodology to afforestation in the Eddleston Water catchment (Dittrich et al, 2019). The methodology uses data from the UKCP09 weather generator to derive probabilities of different climate pathways overtime and uses a simplified real options method to appraise plans under them. The modelling of afforestation benefits takes into account the lag times between planting and benefits. Applying the methodology produces an adaptive planting strategy that is significantly cheaper than planting for the worst-case scenario. The study is based on observational evidence from the Eddleston Water project on the impact of afforestation on flood risk.

- Results from Eddleston Water show that NFM can play a complementary role alongside property-level protection or other flood reduction measures. While afforestation variants provide some flood regulation benefits, none are found to significantly reduce the effects of a major flood such as a 1% AEP event.

- **Without consideration of co-benefits, NFM measures might look economically inviable**: Considering only flood benefits, investment in riparian woodland delivers a positive net NPV only under low and central climate change scenarios. When ecosystem service benefits (in particular CO_2 sequestration) are taken into account, a positive net present value from planting is shown under all climate change scenarios.

Ways in which the appraisal might be expanded:

- **Development of whole catchment models could allow modelling of a full range of flood risk management measures.** A whole catchment model for Eddleston Water is currently being developed by JBA. This will provide for exploration of risk under multiple climate change scenarios and considering the effect of multiple mitigation measures, including combinations. The model will be calibrated using data from Eddleston Water. It is valuable to include results from similar models on the full Tweed catchment as well, as flooding in Peebles is influenced by the water levels in the Tweed. Where peak river flows from the Tweed and Eddleston coincide, higher flood levels may be expected.

- Such a model could account for specific attributes of NFM that are relevant in decision making. These include co-benefits, as well as considerable uncertainty in the efficacy of NFM.

Exemplification of general issues:

- The case study shows the value of combining various measures and considering whole systems when carrying out economic appraisals, as per best practice for adaptive pathways: While direct defences for Peebles are not economically viable in isolation they provide a Benefit Cost Ratio above unity when combined with the preferred option on the River Tweed, due to synergies between the two schemes.

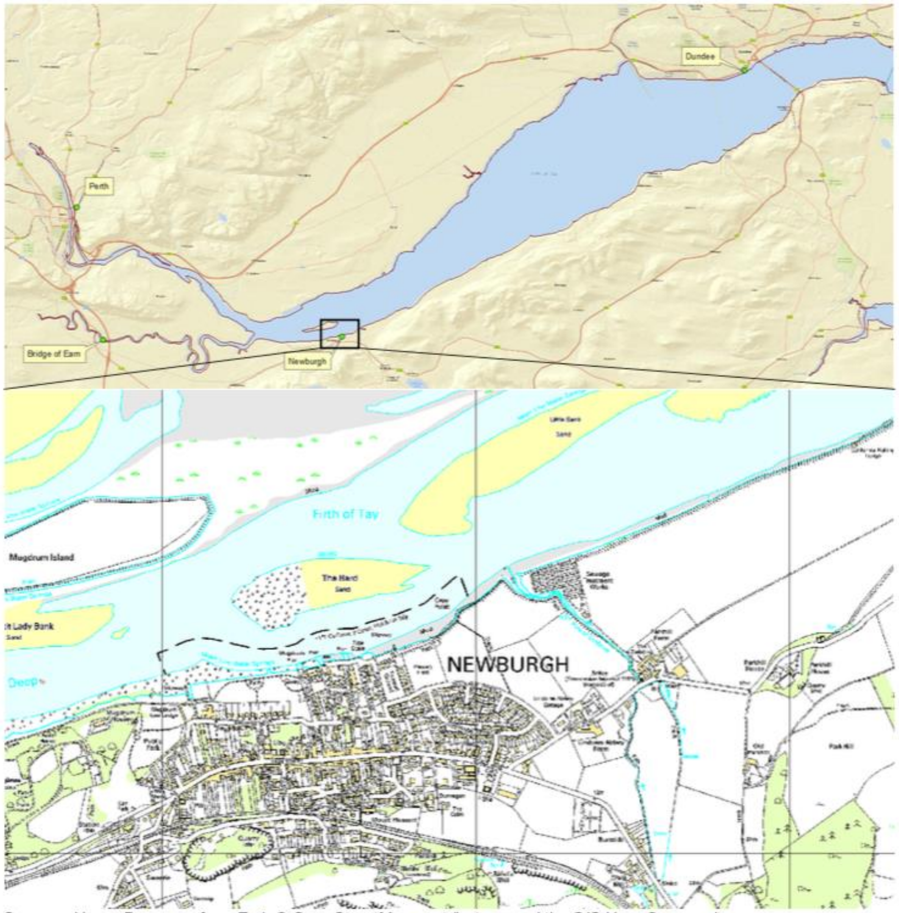
Newburgh

Background

Newburgh is a small coastal town on the south bank of the river Tay, with a population of around 2,000. Newburgh is within the ‘Tayport and Newburgh’ Potentially Vulnerable Area, and the FRM Strategy reports Newburgh being at highest risk from fluvial and coastal flooding. A Shoreline Management Plan (SMP) is in place.

Mott MacDonald was commissioned by Fife Council to produce a feasibility study to identify coastal management options to reduce the risk of coastal flooding and to manage coastal erosion in Newburgh. The flood protection study assesses options for reducing flood risk, and considers several aspects including economic, social and environmental impacts. The study was completed in August 2017. The study considers two flood cells independently: the town of Newburgh and agricultural land east of the Pow of Lindores.

Figure 14. Map of Tay Estuary and Newburgh



Note: Upper Basemap from Esri, @ OpenStreetMap Contributors and the GIS User Community, Lower Base map – Ordnance Survey 1:10,000

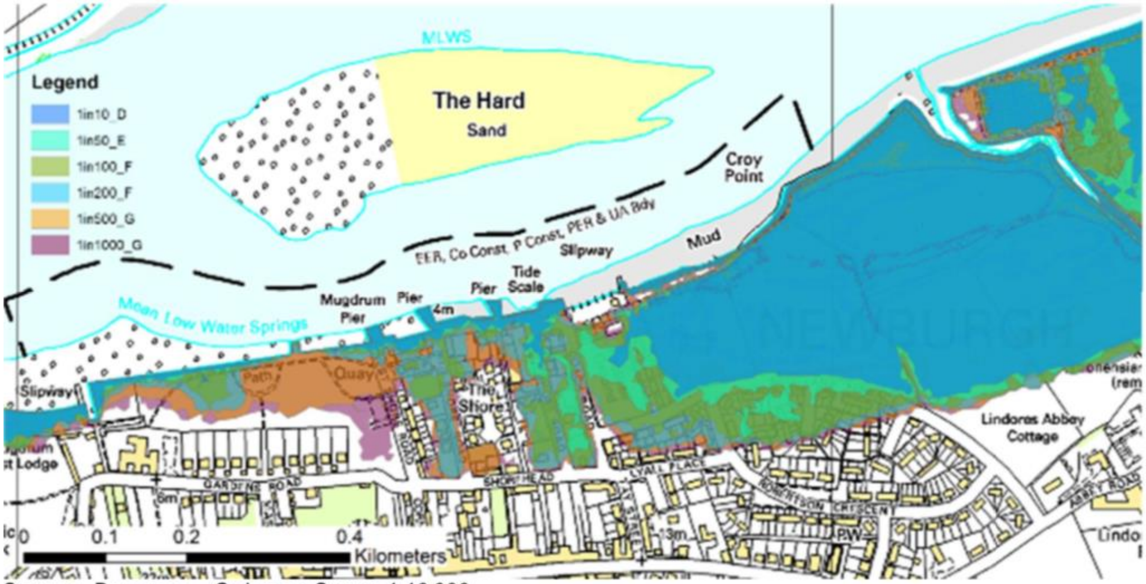
Source: Mott MacDonald

Current risks

The frontage of the town of Newburgh is currently at risk of coastal flooding during storm events and extreme high-water events. Due to its semi-enclosed nature on low ground along the river banks of the Firth of Tay, the coastal processes are dominated by river and tidal flow, rather than waves(Mott Macdonald & Fife Council, 2017a). There is mixture of manmade and natural coastal defences along the frontage. Secondary flood risks arise from fluvial and surface water flooding.

High sea level events have caused flooding of access roads and adjacent areas. Assets in Newburgh town at risk from extreme events include housing, non-residential property, roads infrastructure, recreational areas and amenities. For the area east of the Pow of Lindores, low-lying agricultural land and a Scottish Water wastewater treatment works are at risk of flooding, but no residential or commercial properties are exposed. Currently, flooding does not occur on a normal spring tide.

Figure 15. **Summary of present day worst case flood extents**



Source: Base map – Ordnance Survey 1:10,000

Source: Mott MacDonald, 2016

Future risks

Flood risk might significantly increase over time due to climate change for both Newburgh town and the agricultural land east of the Pow of Lindores. The coastal risk assessment carried out by Mott MacDonald includes hydrodynamic processes, sediment processes, review of historic flooding, review of previous flood assessments, shoreline change and flood modelling assessing the present and future flood risks (including Joint Probability Analysis between extreme water levels, extreme river flows and extreme wind speeds to account for wind generated waves).

The change in flood risk differs according to the climate change scenario considered. The study examined flood risk in 2116 under medium and high emissions scenarios UKCP09, in both cases considering 95th percentile sea level rises. These are shown in Table 18. Modelling of the medium emissions scenario suggests that flooding during normal spring high tide will be limited to agricultural areas with no residential or commercial properties flooded. However, under a 95% high emissions scenario, overtopping of the current defences is expected to occur during normal spring tide, causing extensive flooding of properties. Under both medium and high emission scenarios considered, a significant number of properties are at risk from more extreme events. Figure 16 shows the flood extent of a modelled 1 in 200 event under both present day and future scenarios.

Table 18 **Sea level rise relative to base year of 2008**

Scenario	SLR to 2116
Medium emissions scenario from UKCP09, 95%ile	+ 0.65m
High emissions scenario from UKCP09, 95%ile	+ 0.83m

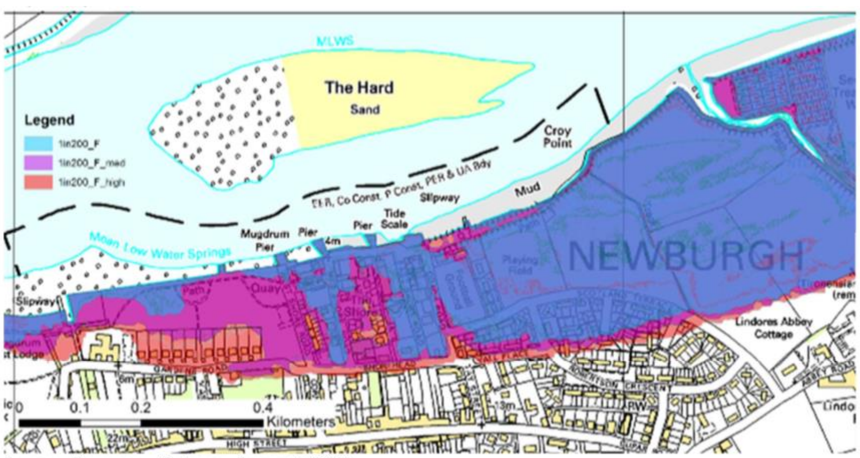
Source: Mott McDonald

Table 19 Number of properties at risk

Return period	Residential: Present day	Residential: 2116 Medium Emissions Scenario	Commercial: Present day	Commercial: 2116 Medium Emission Scenario
1 in 10 year	4	102	0	4
1 in 50 year	11	119	0	4
1 in 100 year	46	129	0	4
1 in 200 year	81	142	4	4
1 in 500 year	104	159	4	4
1 in 1000 year	115	168	4	4

Note: 2116 scenario assumes no change in the total number of residential or commercial properties in Newburgh
Source:

Figure 16. Summary of 1 in 200 year 2116 flood events, including comparison with present day 1 in 200 year event



Source: Base map – Ordnance Survey 1:10,000

Note: Blue: current 1 in 200 event, purple: 2116 1 in 200 event under medium emission scenario, red: 2116 1 in 200 event under high emission scenario
Source: Mott MacDonald

Value of adaptive planning

The flood study suggests there is no rationale for the development of a 'precautionary' flood protection scheme in the present day. The preferred option was defined to provide protection against a 1 in 200 year event under the 95th percentile sea level rise from under a medium emissions scenario, with 0.3m/0.6m freeboard for walls/embankments. As a robustness test, the effectiveness of the option was tested under the high emissions scenario, where it was found that these also provide protection against 1 in 200 year events in the high emissions scenario. However, since there are a limited number of properties affected by more frequent return period events in the present day there is little short-term benefit to the scheme. The economic appraisal calculates the Benefit Cost Ratio of constructing the preferred option now to be 0.63.

Delayed or phased construction provides a higher Benefit Cost Ratio (BCR) than building to a precautionary level now. Since the majority of properties are only at risk of flooding after 50 years' increase of water levels, delaying the scheme for 50 years provides a significantly higher BCR ratio. The study also considers building to a 1 in 200 year Standard of Protection now, and raising the level to 1 in 200 years standard of protection plus climate change in 50 years' time. As shown in Table 20, this provides a BCR ratio of 0.88.

Table 20 .Options appraisal results of time-based interventions

Intervention	Damages assumption
Baseline: 1:200 + CC scheme built in year 1	Damages calculated from modelled 1:200 + CC defences in place
1:200 + CC scheme built in year 20	Do Minimum Damages occur until year 19, after damages calculated from modelled 1:200 + CC defences in place
1:200 + CC scheme built in year 50	Do Minimum Damages occur until year 49, after damages calculated from modelled 1:200 + CC defences in place
1:200 scheme built in year 1, raise to 1:200 + CC in year 50	Damages calculated from modelled 1:200 + CC defences in place (same as Baseline – this results in an underestimate of damages in the first 50 years as the residual flood risk of 1:200 + CC SoP would be greater than 1:200 SoP)

Note: The economically viable options with a BCR>1 are highlighted in green.
Source: Mott MacDonald (2017

In the short term, the Council reported plans to implement property-level protection (PLP) and raising flood protection awareness amongst its citizens. This will include promoting awareness of SEPA flood warnings and undertaking public events to educate the public about measures they can take to protect their homes from floods.

Vivid Economics has undertaken a high-level modelling exercise to demonstrate the potential value of adaptive planning in Newburgh. Taking information from the appraisal study, this project has tested the value of adaptive vs non -adaptive approach. The model shows that an adaptive approach, whereby defences which offer a high level of protection are only built once sea level rises reach a tipping point provides better value than building such defences now. The model is set up as follows:

- There are four 25-year time periods: 2020-2045, 2045-2070, 2070-2090 and 2090-2120.

- In each time period, the sea level might rise between 0cm and 74cm, with 5th and 95th percentile rises 9.25 and 64.75 cm respectively, corresponding to the medium emission scenario range from UKCP09. Sea levels have been modelled as either remaining constant (probability one third), increase 9.25cm (probability one third) or increasing 18.5cm (probability one third) in each period in order to match the distribution from UKCP09.

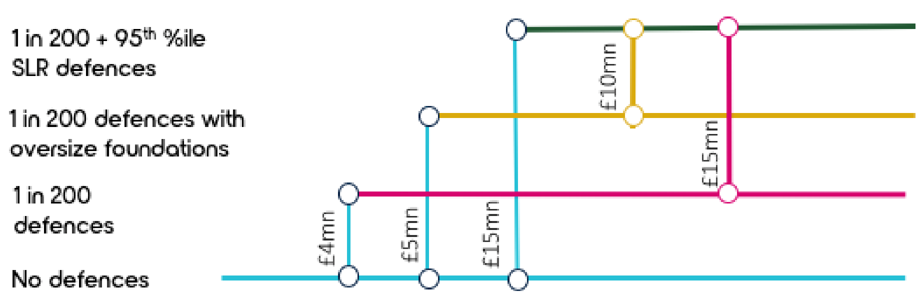
- Annual Average Damages have been calculated for present day conditions at 64.95cm SLR by applying the Weighted Annual Average Damage approach from the Multi-Coloured Manual to the residential properties at risk of flooding according to the flood study. Linear interpolation has been applied to calculate risks at intermediate levels of sea level rise.

- Defences can be built to protect against 1 in 200 present day events or against 1 in 200 + 95th percentile climate change uplifted events. There is an option to build directly to the higher SoP, or to build to protect to the lower SoP but include oversized foundations to facilitate raising the wall if later desired. The resulting possible adaptation pathways are shown in Figure 17.

- For the sake of modelling complexity, no discounting has been applied when calculating the total values of either costs or benefits. Applying discounting is not expected to change the qualitative conclusions of the modelling exercise.

- This project used a process of backwards induction to 'solve' the full decision tree at each of the four periods, considering each possible adaptation measure. It was found that the optimal plan consists of building the adaptable 1 in 200 defence in the first period, and raising this if the SLR increased to 18.5cm. This optimal plan provides a 5% higher expected Net Present Value than any single action taken today and also provides for flexibility.

Figure 17. Potential adaptation measures and costs of moving between the measures



Note: Costs are illustrative
Source: Vivid Economics

Lessons from case study

The case study shows that adaptive planning is both feasible and valuable even in small communities. The case study and this report take a parsimonious approach to appraising simple adaptive plans and show that these can be more cost effective than non-adaptive approaches. A review of the materials presented and interviews with those involved in conducting the appraisal highlights the following wider considerations.

Aspects of the appraisal that could be applied elsewhere:

- **The Newburgh case study shows a simple method to carry out appraisals of time-based interventions.** Undertaking a scheme to provide a 1 in 200 year plus climate change level of flood protection is not currently justified for neither Newburgh Town nor the adjacent agricultural areas, but the case will increase if sea levels rise significantly.

- Transferring models developed by consultants to Responsible Authorities can reduce reappraisal costs, providing a means to react to new climate change information when it becomes available. Fife Council will be able to use model outputs to reappraise Newburgh in the future, for example incorporating UKCP18 sea level projections.

Ways in which the appraisal might be expanded:

- Although an optimal adaptive plan is likely to take account of future social and economic changes, these were considered to add too much complexity to the modelling for inclusion. Research is likely to be required on expedient ways to combine uncertainty about socio-economic scenarios with uncertainty about the future climate.
- A fuller account of uncertainty, including probabilities of scenarios, would allow for a more accurate valuation of adaptive plans. This valuation would show the trade offs between more flexible approaches, which can tailor interventions to emerging information on risks, and committed approaches in which infrastructure costs can be lower.

Clyde River Corridor

Background

The Clyde River Corridor covers the part of the River Clyde between Glasgow city centre to the terminal areas around Greenock/Gourock. Glasgow is located along the transition reach between the tidal and fluvial influences and flooding along the River Clyde can be both fluvial and tidal. Much of the land around the Clyde River Corridor is used for industry and many residential areas are located close to the river. There are new developments at Finnieston, along the north bank at Lancefield Quay and Yorkhill, and areas further downstream such as the Glasgow Harbour development. There has been serious tidal flooding in areas downstream of Glasgow in the past.

The case study is based on research commissioned by Climate Ready Clyde and carried out by Paul Watkiss Associates. The research develops outline adaptation pathways on coastal flooding for the Clyde Corridor. The draft research report, hereafter referred to as 'the PWA report', has been shared with the project team for inclusion in this report.

Figure 18. The Clyde Corridor

Source: Google Maps

Current risk

In Glasgow City, Annual Average Damages from flooding are estimated at £10m, with 13,000 residential and non-residential properties at risk of flood. Across the whole region, Annual Average Damages are estimated at £67 million. Of this, £27 million is due to coastal flooding, £19 million to fluvial flooding and £20 million to surface water flooding.

Future risk

The risk from coastal floods in the Clyde River Corridor is expected to increase with climate change. Future flood risk might be affected by changes in**:**

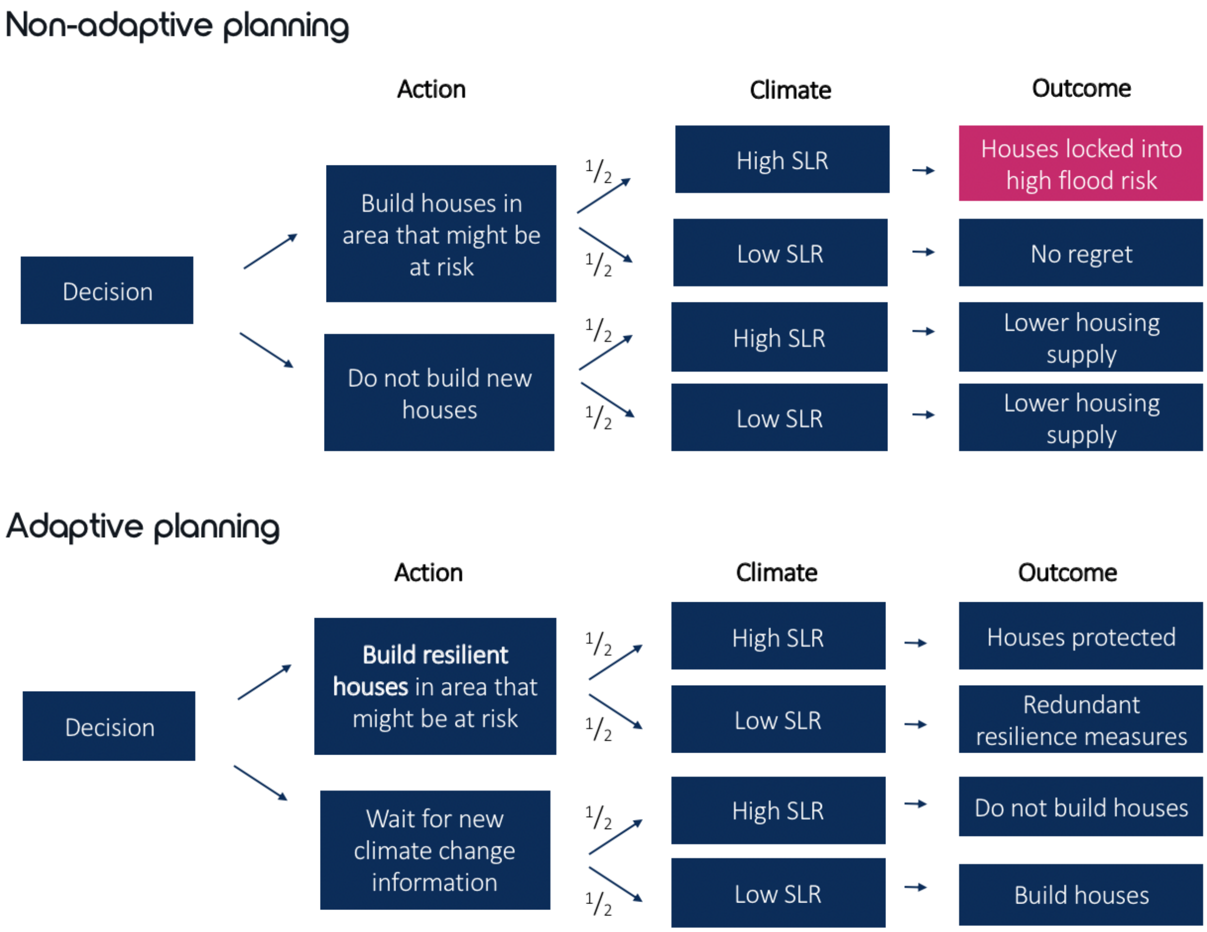
- Relative sea levels
- Storm surges due to wind and atmospheric forcing of the sea surface
- Wave heights
- Coastal morphology and sediment supply
- Population, demographics and asset value

The adaptation pathways developed in the PWA report focus on the effect of sea level rise on flood risk. The 95th percentile estimate for sea level rise by 2080 under the UKCP09 'high' emissions scenario is 0.47m. SEPA estimates that this level of sea level rise would roughly double the number of residential and non-residential properties at risk of coastal flooding. There is considerable uncertainty as to the impact of climate change on storm surges, wave height and extreme waves.

Value of adaptive planning

Significant investment in housing and infrastructure is expected in the near future, which could affect long-term flood risk. It is estimated that population growth will result in a 10% increase in the number of households between 2012 and 2030 (Strategic Development Plan, 2017). The Glasgow and City Valley Strategic Development Plan (Clydeplan) estimates that 91,860 houses will be required by 2029 and sets out plans for a Development Corridor, running east-west through the city parallel to the River Clyde. Depending on exactly where development takes place building could significantly increase flood risks in the region, as once assets are built they are 'locked in' over the long term. On the other hand, the decision to not build new homes in areas which might become at risk of flood might be regretted if climate impacts on flood risk are less extreme. The value of adaptive planning in this situation is illustrated in Figure 19 below, where building resilient assets in anticipation of future flood risk, or waiting for new climate change information before making a decision to build, can lead to better outcomes under all climate futures.

Figure 19. Adaptive vs non-adaptive planning



Source: Vivid Economics

In the context of changing financial regulation on risk disclosure, an adaptive approach to flood risk management could incentivise more appropriate development. Regulations on financial disclosure of climate related risks are tightening, with the Prudential Regulation Authority for Banks leading plans to require building societies and insurance companies to report and disclose the financial risks associated with the physical risks of climate change. A recent initiative to understand impacts of climate change on real estate investment trusts (REITs) identified Glasgow to be particularly exposed to climate risk (Four Twenty Seven & GeoPhy, 2018). These ratings have the potential to significantly affect risk and investment appetite from investors and to increase pressure on cities to reduce these risks to help secure future investment, economic development and growth. An adaptive approach to flood risk management, which manages risk more efficiently and can communicate future risks more transparently than traditional approaches, could therefore offer substantive support to the Clyde region's wider economic development (Climate Ready Clyde, 2019).

Feasibility of adaptive planning

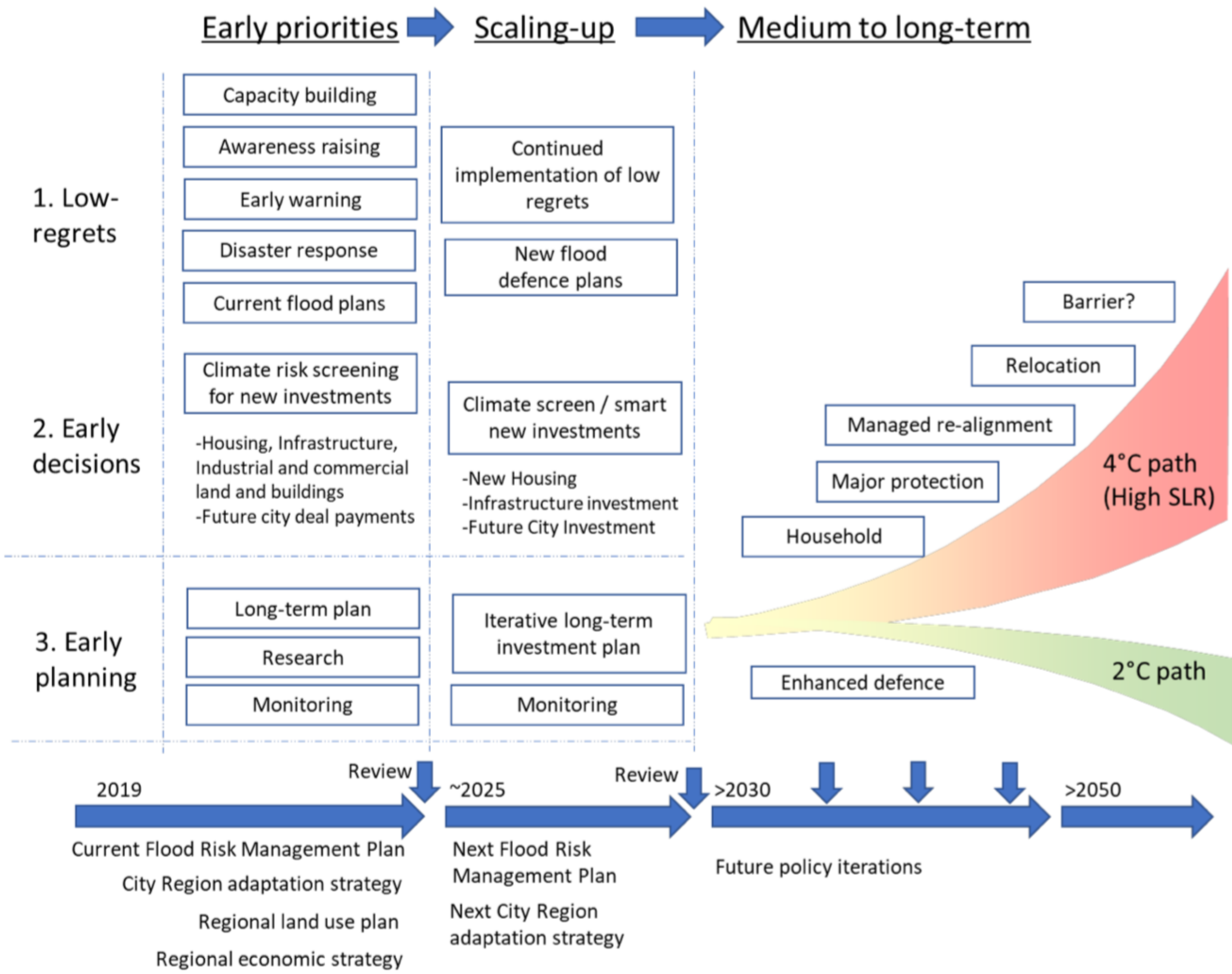
The PWA report develops two types of adaptive pathways, which are considered in turn:

- A high-level medium-term (to 2050s) adaptation pathway for the Clyde Corridor. This involves the identification of early adaptation measures and sequencing of adaptation measures over time.
- A more in-depth adaptation route-map, using thresholds and tipping/trigger points.

The PWA report generates an illustrative high-level medium-term (to 2050s) adaptation pathway for coastal adaptation in the Clyde Corridor, which is shown in Figure 20**.** The adaptation pathways have been generated by identifying actions for the next five years and then sequencing subsequent adaptation options. Following the ‘priorities for early adaptation’ from the second UK Climate Change Risk Assessment, actions for the next five years have been identified with the following aims:

- Implement early ‘low’ or ‘no-regret’ measures. These might include capacity building, enhanced risk preparedness, low cost interventions or risk spreading.
- Ensure adaptation is considered in decisions that have long lifetimes, such as new housing or infrastructure developments. An appropriate response to future risk might be changing the location of new developments, demanding enhanced planning review on at risk sites or making infrastructure adaptable to changing risks. For example, mandating that new houses built in areas which might become at risk of flood include property-level protection measures can help enhance resilience.
- Set out a process for decision making where interventions have long lead times or where information, monitoring, research and pilots could help inform future decisions. Such steps include measures to cope with rising risks, such hard coastal flood defences, green or ecosystem-based adaptation (green-grey infrastructure, flood buffer zones, etc.), coastal realignment (including managed realignment), relocation and major barrages.

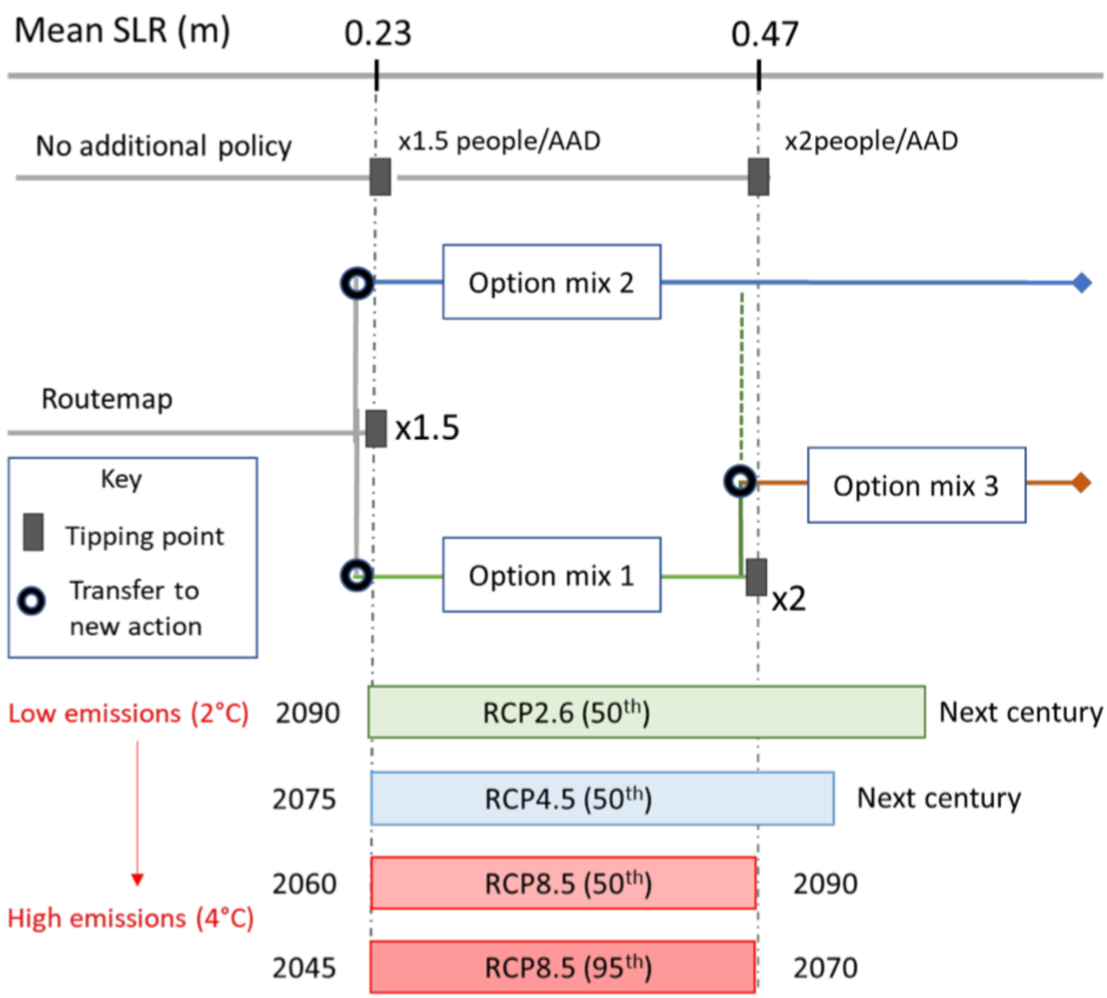
Figure 20. High-level adaptation pathway showing early priorities for coastal adaptation



Source: Paul Watkiss Associates

A more in-depth adaptation route-map using tipping points is shown in Figure 21. First, tipping points are chosen, defined in terms of increases in damages and following the method set out by Ramm, Watson, & White (2018). The initial tipping point is defined to occur when flood damages reach 1.5 times their current levels; this is estimated to occur with 0.23m of sea level rise. A second tipping point is defined as occurring when flood damage rises to two times their current levels, which is estimated to occur at 0.47m of sea level rise. Depending on how climate change unfolds, the date at which the tipping points are reached (if at all) will vary. Under the adaptation route-map, investment in new flood protection would be undertaken prior to tipping points being reached (taking into account lead times for new measures). The PWA report considers two sets of measures which could be introduced: a package which protects houses affected by higher risk of flooding (option mix 1) or a more comprehensive set of measures which provide a very high level of protection to the whole of Clyde Corridor (option mix 2). At the first tipping point, the decision maker would choose between these two option mixes. At the second tipping point, the action taken would depend on what had been carried out at the first tipping point. If mix 2 had been chosen, no additional adaptation measures would be necessary since the level of protection would already be high. If mix 1 had been chosen, a set of additional adaptation actions would be carried out (option mix 3).

Figure 21. Illustrative adaptation route map for coastal flooding for the Clyde Corridor



Source: Paul Watkiss Associates

The mixes of measures differ in their degree of flexibility. Mixes 1 and 3 are likely to comprise more flexible interventions in new flood protection, which could include integrated green-grey infrastructure or natural based systems, combined with household level resilience and planning measures for new development. Mix 2 might include more transformative structural options, such as a moveable barrier structure for the inlet or estuary. For example, for Glasgow the need for structures protecting against storm surges is likely only to be relevant in the long-term (after 2100) and only under exceptionally high sea level rise.

Lessons from case study

The investment required for adaptive planning is most likely to be worthwhile in larger study areas, where there are multiple policy objectives to be considered and more assets are at risk. Full economic appraisals of adaptive approaches can require a large amount of analytic effort, which might be prohibitive for smaller study areas.

A review of the materials presented and interviews with those involved in conducting the appraisal highlights the following wider considerations.

Aspects of the report that could be applied elsewhere:

- **A pragmatic approach to identifying tipping points is to start with default levels of protection**. These can be based on an acceptable level of risk (e.g. the 1 in 200 annual exceedance probability for households) or design standards (required protection expressed as capacity for peak flows and draining). However, choice of acceptable level of risk is essentially a political decision, and stakeholders might have different opinions on the level of ‘acceptable damage’.

- Route maps are a useful way of presenting information and communicating the need for iterative approaches and long-term thinking.

Exemplification of general issues:

- **Multiple, interacting flood risks complicate the design of flexible adaptation approaches and require significant time and resources**. The Clyde River Corridor faces particularly complex and interacting flood risks, including coastal flooding, river flooding, surface flooding and erosion. The project team stated that combining all flood risks into an overall master pathway that captures all risks and tipping points would result in extremely complicated route-maps, requiring detailed modelling and considerable time and resources. The complexity also makes it difficult to provide a holistic approach that accounts for other factors that affect exposure such as economic development, inward investment and land use planning.

- **Accounting for uncertainty over future development can be as important as accounting for climate change.** The reasons for this are twofold: first, in expanding urban areas, uncertainty over development patterns can have a comparable effect on uncertainty over flood risk to climate change; and, second, by setting out an adaptive plan where policy makers respond predictably to future development, planners can incentivise development that avoids undue increases in risks.

- **Limited information around future climate risks makes it difficult to identify tipping points**. The PWA report uses UKCP18 projections and only considers coastal flooding as a consequence of sea level rise. It presents illustrative tipping points associated with unacceptable levels of future risk and damages only. Future flood risk will also vary with storm surge and wave heights, where there is considerable uncertainty as to the impacts of climate change.

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