ADAPTIVE PLANNING STANDING THE TEST OF TIME: THE THAMES ESTUARY

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ABSTRACT

The UK Environment Agency's *Thames Estuary 2100 flood risk management plan* (TE2100) is an adaptive flood risk management plan developed to protect London and the lower Thames River from flood risk through to the end of the 21st century.

Published in November 2012 following a six year programme of studies, TE2100 was the first major UK flood risk management plan to place adaptability as a fundamental requirement, in recognition of the uncertainty of pace and scale of changes that might occur with climate change. 5 years on, TE2100 is still viewed internationally as an exemplar approach to adaptive flood risk management on a significant scale.
What were the key elements that led to the success of this project which have stood the test of time in this vitally important and rapidly changing area? David Ramsbottom was the Environment Agency's technical lead for the development of TE2100 and so will provide unparalleled insight into the delivery of TE2100 and the attributes that have resulted in it being identified as an exemplar approach to adaptive flood risk management planning. He will provide an overview of the method and how it was applied in TE2100.

Importantly, with 5 years hindsight and further development in adaptive planning, and with TE2100 having moved into an implementation phase, David will reflect on things which would be considered differently if the project was starting now.

Many of the challenges facing major urban centres in New Zealand share similarities with those addressed in TE2100; including sea level rise and varying flood sources, large populations at risk, uncertainty, ageing infrastructure and complex planning and economic environments.

This paper will use the TE2100 example to explore the fundamentals of adaptive planning and identify similarities and lessons that could help New Zealand as central and local government plan for climate change.

KEYWORDS

TE2100, Adaptive flood management plan

PRESENTER PROFILE

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Matthew is a Principal Water Engineer at Jacobs in New Zealand. He has 26-years' experience in the water sector, with experience in the storm water sector ranging from flood management strategy development through to detailed design and implementation.

DEFINITIONS

The paper uses terminology that is consistent with UK practice but may be unfamiliar to some readers. For example, the term 'flood risk management' refers to the overall process of controlling flooding (sometimes referred to as 'flood protection') and mitigating the effects of flooding.

The following definitions are used in the paper:

Response. A 'Response' is an individual flood risk management measure, for example a barrier, a length of raised defence or an emergency plan for a community.

Portfolio. A 'Portfolio' of responses is a number of responses which, when combined together, provide a complete flood risk management solution for a particular increase in sea level and/or fluvial flow.

Option. An 'Option' is a number of portfolios which, when implemented in sequence, provide a complete flood risk management solution for the duration of the flood risk management plan.

Pathway Response. A 'Pathway Response' is a response that affects the 'pathway' or route of flooding. These include flood defences and barriers.

Receptor response. A 'Receptor Response' is a response that affects the receptors on the floodplain. The receptors include people and assets. Receptor responses include flood warning and resilient building construction.

Receptor responses address the residual risk that still exists after the implementation of pathway responses.

The relationship between flood probability, portfolios of responses and options is shown on Figure 1. In the TE2100 Plan, options were designed so that a particular probability of flooding is not exceeded taking account of climate change. It was possible to use probability because the benefit cost ratio for the most likely options all exceeded 40. This means that it was not necessary to design the options based on flood risk (probability x consequence) because in all cases the benefits were very high.

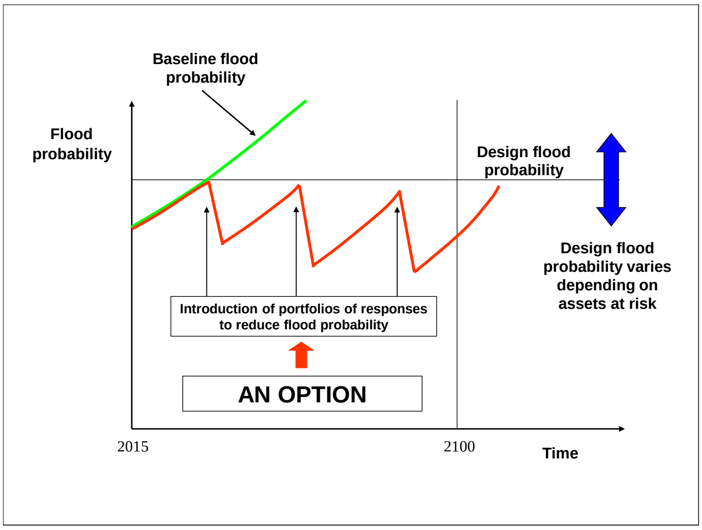

Figure 1 Definition of a flood management option

If the method is applied elsewhere, it is recommended that flood risk should be used in place of flood probability even though the calculation is more complex. This is because the options must be justified economically and are likely to be more marginal than on the Thames estuary. In this case an option would be designed so that a particular risk of flooding is not exceeded (for example, a particular value of Annual Average Damages).

1 INTRODUCTION

The River Thames in the south-east of England has a catchment area of about 15,000 km^2. The lower 100 km of the Thames between Teddington (in west London) and the sea is tidal and is referred to as the Thames estuary. The estuary passes through central London. The estuary has an extensive floodplain covering about 350 km^2 which includes large parts of London together with many smaller towns, industrial areas, port facilities and grazing marshes.

The floodplains of the Thames estuary are protected by a major system of flood defences including about 350 km of flood banks and walls, and many flood control barriers and gates including the Thames Barrier (Figure 2), which prevents high surge tides flooding the centre of London.

Figure 2 The Thames Barrier

The Thames Barrier was designed in the 1970s and included an allowance for sea level rise until 2030. The Thames Estuary 2100 (TE2100) Plan was implemented in order to provide a flood management plan that takes account of the need to replace or upgrade the Thames Barrier (Lavery and Donovan 2005). The Plan was developed between 2005 and 2010, and implementation commenced in 2012. In view of the importance of London and the Thames estuary, climate change adaptation was a key driver in the development of the Plan (Reeder *et al* 2013).

2 SUMMARY OF THE APPROACH FOR ADAPTIVE PLANNING

2.1 PURPOSE

The management of climate change is an important objective for flood risk management planning. It requires an adaptable approach where measures are introduced at different times to limit the increase in flood risk due to climate change to acceptable values.

The purpose of the approach is to identify adaptation options that can be implemented in stages as the climate changes in order to prevent flood probability or flood risk (i.e.

probability x consequences) increasing above a specified level. The description in this section refers to flood probability but the method is equally applicable using flood risk. Flood risk is however more complex to calculate.

Climate change is projected to increase the amount of flooding from increases in sea level, rainfall and river flows. Flood probability will therefore increase until a certain threshold level (the maximum acceptable flood probability) is reached and interventions are needed to reduce the probability of flooding. After the interventions to reduce the probability have been implemented, the flood probability will reduce but will then increase once again over time until the specified threshold is reached, and another intervention to reduce the probability will be needed. This cycle is repeated as indicated on Figure 1. Thus each option will consist of a sequence of interventions implemented over time.

2.2 PRESENT AND FUTURE RISKS

The first step in the approach is to establish the present day flood probability and the present day design probability. The present day flood probability is normally defined by hydraulic modelling and the design probability is normally specified.

Climate change will increase the amount of flooding as a result of sea level rise and increases in storm surge, rainfall and river flows. Climate change science is used to develop a range of projections for these drivers including a 'best estimate' projection (normally based on current government guidance where available), a low estimate and one or more 'high' estimates, which indicate what might happen under extreme conditions. This may require joint probability analysis where two or more drivers combine to cause flooding.

The 'high' estimates are used to set the long-term adaptation requirements, so that adaptation actions designed for smaller changes can be further adapted without regrets if required in the future to cope with the worst scenarios that could potentially occur. The concept of 'limit of adaptation' is used to identify the point where no further adaptation is possible, to set the upper limit on adaptation options.

At this stage factors that can affect the flood analysis should be identified, for example the impact of climate change on flood hydrograph volume which would affect the design of flood storage responses, or the effect of tide curve shape on estuary water levels.

2.3 ANALYSIS METHOD

The approach to the analysis of the particular physical system must then be decided. For complex systems such as the Thames estuary it may be simpler to divide the system into areas where the interdependence between the sources of flooding is relatively small. For example, tributaries on the Thames estuary were treated separately from the estuary and combined later. This simplifies the analysis and helps to provide a clear audit trail.

The maximum acceptable flood probability is represented by the 'Standard of Protection' (SoP), which is the level of protection provided by the flood defences expressed either as an annual flood probability (%) or a return period in years. This sets the threshold values of acceptable flood probability for the flood defence system that should not be exceeded. This is often expressed in terms of Level of Service, for example 'no above floor level flooding in a 2% Annual Exceedance Probability (AEP) event'.

The baseline is then defined in terms of flood water levels for different flood probabilities, existing flood defence levels and the existing Standards of Protection. It is necessary to take the 'freeboard allowance' into account when assessing the Standards of Protection. This is the allowance added to flood defence crest levels to take account of uncertainty.

Other constraints that affect the analysis should also be defined at this stage. For example, the maximum allowable annual number of closures of the Thames Barrier was an important factor in adaptation planning for the Thames estuary.

Modelling of future scenarios is undertaken to determine the thresholds when interventions are needed to keep the flood probability within acceptable limits. Flood management interventions are then investigated to identify the best options for adapting the flood management system.

2.4 DEVELOPMENT OF FLOOD MANAGEMENT OPTIONS

The types of flood management responses that would be suitable are identified by a process of screening all the available responses. In order to reduce flood probability a portfolio of responses is normally required consisting of several responses, for example a new flood barrier combined with new defences and defence raising.

Portfolios of responses are then identified and assessed to identify those portfolios that are most suitable. The assessment might include hydraulic modelling together with high level environmental and economic analysis. The most suitable portfolios are plotted on a diagram which shows the amount of change in the relevant driver of flooding that they can accommodate. By plotting all portfolios on the same diagram, combinations of portfolios to manage short, medium and long-term impacts of climate change can be identified. These form the options for flood risk management.

The portfolios of responses are refined by hydraulic modelling and the thresholds when the portfolios reach their maximum limit of flood risk are identified. The portfolios are also improved using information on local detail, feedback from stakeholders and feasibility studies where required.

It is also necessary to link the adaptation requirements with other objectives of a flood risk management plan. This will include linking the adaptation requirements with the estimated residual life of existing defences and the estimated design life of new defences. For example, if a defence in poor condition requires raising in the near future, a new defence might be a better option than adapting the existing defence.

The final options should be suitable for the climate change allowances anticipated within the timescale of the flood management plan, but should also be adaptable to more severe longer-term future conditions. The options are then appraised to identify the preferred option. Monitoring of climate drivers and other key indicators (for example, flood defence condition) is essential so that the plan can be updated in the future based on the most up-to-date estimates of climate change and any new government guidance on climate change. This will ensure that improvements are implemented when required.

2.5 APPLICATION OF THE METHOD

The approach to adaptation outlined above is theoretically applicable to any situation. The essential elements of the method include the following:

- An understanding of the potential extreme impacts of climate change that could occur.
- An assessment of all potential responses for managing the increase in risk, and identification of the responses that would be needed to manage the potential extreme impacts of climate change.
- Development of portfolios of responses for managing the increase in risk in incremental steps that avoid 'no regrets' actions as far as possible.

- Integration of the measures required for adaptation with other aspects of flood management planning, particularly the work needed to maintain and improve existing defences.

There is scope for introducing optimisation methods into the development of adaptive options for flood risk management, for example using the Real Options approach (Woodward et al. 2013). This approach could become a viable method of assessing options, particularly with increasing computer power and the evolution of better data sets. However the analysis is complex and it would be wise to apply it to simple situations before addressing a complex system such as the Thames estuary.

3 APPLICATION TO THE THAMES ESTUARY

3.1 INTRODUCTION

The adaptation method was originally developed for the Thames estuary, and the application is described in this section. The existing flood management system on the Thames estuary is large and complex, with about 350km of fixed defences, the Thames Barrier, five other major flood barriers and numerous smaller structures. The layout is shown on Figure 3.

Some of the factors that complicate the analysis of flood risk management on the Thames estuary are as follows:

- Tidal water levels increase as the tide propagates westwards along the estuary from Southend.
- Tidal water levels are affected by the tide curve shape, particularly for surge tides where the astronomical tide is combined with a surge residual.
- Tidal water levels are affecting by flooding, particularly overtopping and/or failure of defences in the lower estuary that have a lower SoP than further upriver.
- Options must take account of the effects of barrier operation.
- Extreme water levels include combinations of tidal water levels and river flows from the Thames and tributaries. There is also wave action, particularly in the wider lower estuary.

The options for the Thames estuary were developed by a process that included Early Conceptual Options (Environment Agency 2005), pilot portfolios (HR Wallingford 2006a), High Level Options (Environment Agency 2007) and detailed options for appraisal (Environment Agency 2009, particularly Appendix D).

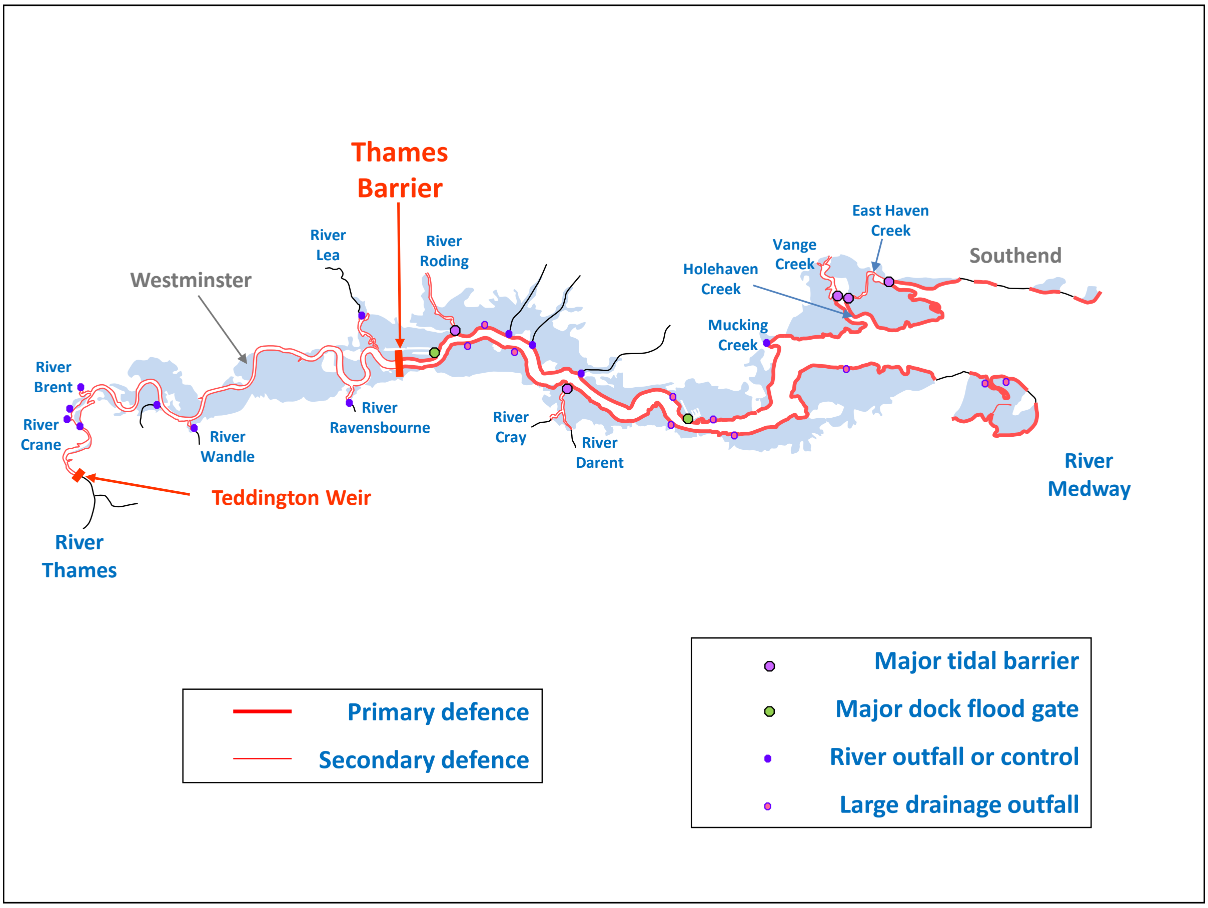

Figure 3 The Thames estuary flood defence system

3.2 OBJECTIVES

The primary objective of the TE2100 Plan was to develop a Flood Management Plan for London and the Thames estuary. Other objectives included adaptation to climate change and management of the existing defences in addition to objectives related to people, the environment and planning (TE2100 2012).

3.3 INITIAL FLOOD RISK

Flood risk was initially assessed without the defences to show the magnitude of the risk and the importance of the defences. The risk was then assessed with the defences in place for both present day and future scenarios including climate change.

3.4 IMPACTS OF CLIMATE CHANGE

A major study was carried out to determine climate change scenarios for use in the TE2100 Plan covering sea level rise, tidal surges, waves, rainfall and river flow (Environment Agency 2009 Appendix L). The main potential cause of flooding is from the sea, and therefore sea level rise was the primary concern. Four sea level rise scenarios were developed which are shown on Figure 4. An important feature of the scenarios is that the rate of increase in the peak surge tide level is greater than mean sea level for three of the four scenarios. Joint probability analysis was also carried out to assess the dependencies between the different sources of flooding (HR Wallingford 2006b).

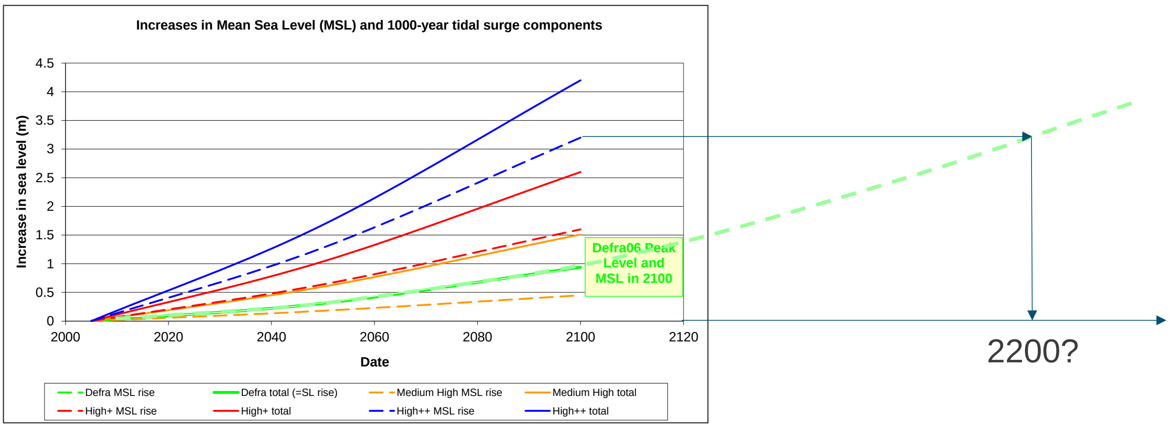

Figure 4 Climate change scenarios for sea level rise

Figure 4 includes the Defra06 climate change scenario that was used in the detailed design of the final TE2100 options. One of the reasons for applying more extreme scenarios is illustrated on Figure 4: whilst the Defra06 government guidance indicates a sea level rise of about one metre between 2005 and 2100, the projection of the scenario shows that the higher sea level rise scenarios will be reached eventually. Infrastructure with a long design life should therefore take account of these higher scenarios in long-term planning. Even when infrastructure reaches the end of its design life, a replacement is likely to be constructed at the same location.

A further variable is the variation in peak tidal water levels along the estuary, which are affected by the tidal water level at Southend and the tide curve shape. Figure 5 shows how peak tidal water levels vary along the estuary. The peak high tide level increases by about one metre from the sea to the Thames Barrier.

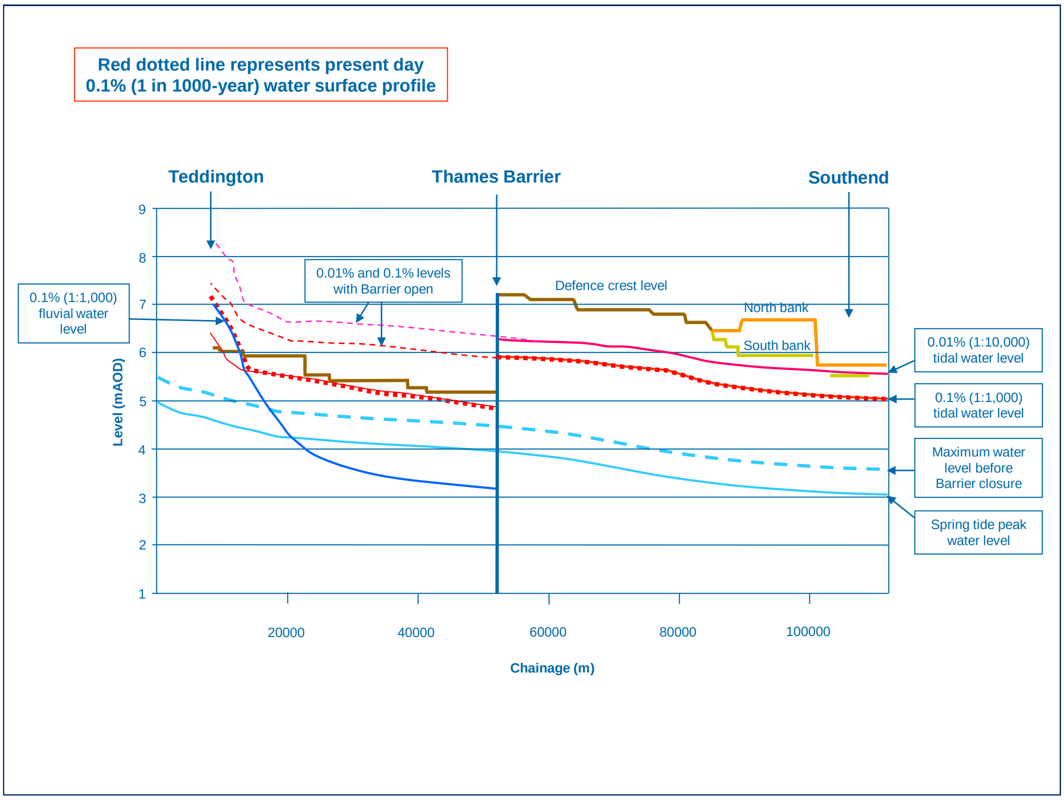

Figure 5 Thames estuary longitudinal section

3.5 OVERALL APPROACH

Dependences between different parts of the flood management system (the Thames, the tributaries and the floodplain drainage systems) were assessed. As the impacts of the tributaries and drainage systems on the Thames are small, it was possible to assess flood risk and flood mitigation measures for each part of the system in turn, in the following order:

1. Thames including interaction between tidal water levels and fluvial flows from the Thames at Teddington, and operation of the Thames Barrier.

2. Tributaries including interaction between water levels on the Thames, fluvial flows and structure operation where relevant (including tidal barriers and outfalls).

3. Drainage systems including impacts of water levels on the Thames.

The approach to climate change adaptation was undertaken in two stages:

1. Use of extreme scenarios to identify the limits of different options and set the long-term adaptation requirements (in the High Level Options).

2. Use of scenarios based on Government guidance for developing the detailed options for appraisal.

3.6 DESIGN STANDARDS OF PROTECTION

The existing Standards of Protection on the Thames estuary were an annual tidal flood probability of 0.1% (1 in 1,000-year return period) in 2030 for most of the estuary but with lower standards (0.5% or 1 in 200 years) in parts of the lower estuary. Fluvial Standards of Protection were lower, typically 1% or 1 in 100 years.

A Policy-based approach was used in TE2100 to determine the design levels of protection. The floodplains were divided into 23 Policy Units, and an appraisal was carried out for each Policy Unit to determine whether flood risk should be allowed to (i) increase, (ii) remain the same (taking the effects of climate change into account) or (iii) reduce.

The resulting design SoP for tidal flooding through London was 0.01% (1 in 10,000-year return period), which represents an increase in the SoP compared with the present day. This will be implemented when the first major improvement to the system is carried out. Developed areas downriver of the Thames Barrier had the same design SoP as at present including defence raising to take account of climate change, and Policy Units with relatively few assets at risk had reduced SoP which were achieved by not raising the defences as the sea level rises and fluvial flows increase until the appropriate SoP are reached.

3.7 THE BASELINE

The baseline was defined in terms of flood water levels along the estuary and flood defence crest levels. Overtopping of some defences occurred for larger events, particularly in the marsh areas in the lower estuary that have a lower SoP than defences further upriver. This affects flood levels along the estuary. It was decided to use a baseline with no overtopping of defences as this produced higher water levels, and was therefore conservative.

Other constraints were defined at this stage including the following:

- Maximum number of barrier closures per year. This was necessary to provide adequate time for maintenance so that probability of failure does not drop below the design standard.

- Limits of defence raising in public areas, particularly central London. A maximum increase of one metre was agreed together with ground raising and landscaping to maintain access and views of the estuary.

- Design life of new structures and residual life of existing structures.

- Habitat creation requirements.

3.8 RESPONSES AND OPTIONS

Flood risk management responses were identified in a process of screening that included hydraulic modelling for some responses, for example the potential for tidal flood storage (Environment Agency 2005). Portfolios of responses were then developed and their effectiveness assessed using hydraulic modelling (HR Wallingford 2006a). Options (consisting of a sequence of responses covering the period to 2100) were then developed. These were refined and the four generic High Level Options (HLO) for managing tidal flood risk are shown on Figure 6.

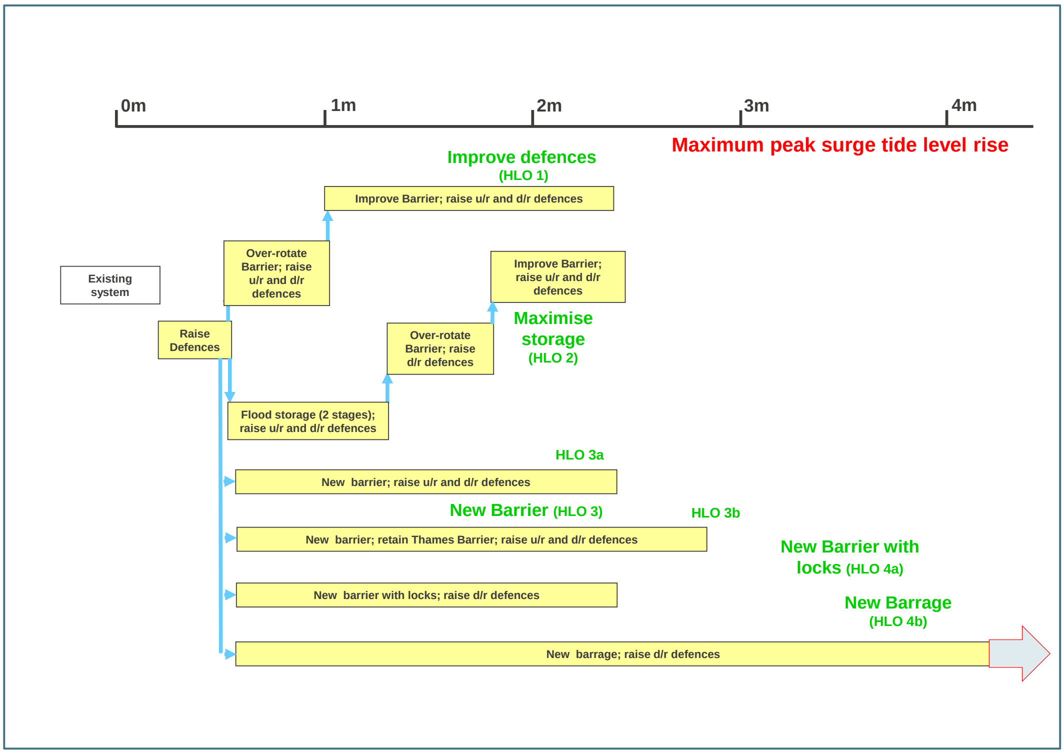

Figure 6 The TE2100 High Level Options for tidal flood management

Figure 6 shows that all options can accommodate a peak surge tide level rise up to about 2.4m. Above 2.8m the barrier with locks or barrage is the only available option. The 2.4m limit is a combination of the maximum annual number of barrier closures and the maximum permissible upriver defence raising, and depends on the change in normal high tide level and not peak surge tide level.

3.9 HYDRAULIC MODELLING

Hydraulic modelling for designing the portfolios of options was simplified in the following ways:

- Initial designs were prepared with no overtopping of defences in order to simplify the analysis. The impact of overtopping on water levels along the estuary was shown to be modest, up to about 0.2m for 0.1% and 0.01% events in the year 2100 (HR Wallingford 2013, Appendix B, Barrier closed case).

- Designs of the best emerging portfolios were then refined with defence overtopping permitted. In this case the floodplains were modelled as reservoirs as the important physical process to be represented was the loss of water over the defences, not flood spreading on the floodplains. This meant that the models could be run relatively quickly.

- Detailed 2-dimensional floodplain modelling was used for the appraisal, where accurate flood spreading on the floodplains was required to identify the consequences of flooding.

3.10 OPTION DEVELOPMENT

The feasibility of the options was assessed in a series of studies covering all aspects of the responses. For example, the feasibility of raising the defences was assessed including the development of outline designs and associated costs.

The portfolios of responses were also improved in stages using the following information:

- Feedback from local option studies, which assessed the implications of the options at a local level

- Assessment against wider objectives including environmental, landscape, social and public amenity requirements

- Feedback from stakeholder consultation

The detailed options were designed for the Defra06 climate change allowances to 2100 (Defra 2006, Environment Agency 2008). The sea level rise projection is shown on Figure 4. The options also took account of other objectives of the TE2100 Plan including maintaining the existing defence system in good condition taking account of deterioration, environmental improvements including habitat creation, public amenity improvements, landscape improvements and links with other riverside developments.

The options were appraised by multi-criteria analysis that included benefit-cost analysis in order to identify the preferred option for managing flood risk on the Thames estuary. The options included 'do minimum' and reductions in the SoP but the value of assets at risk was such that the best options were those that provide a high SoP. The final Plan includes the following stages:

1. The works required to maintain and improve the system of tidal flood defences on the Thames estuary for the period until a major improvement will be needed for the whole system.

2. A major improvement to the system. There are two 'front runner' options: a new barrier in Long Reach or a major upgrade of the Thames Barrier. There will also be extensive defence raising downriver of the barrier whichever choice is made. The Plan currently shows the major improvement as being commissioned by 2070, but this date is likely to change because the actual rate of sea level rise will differ from the projected rate used to develop the Plan.

Figure 7 shows the preferred option for managing sea level rise including the two 'front runner' options that will be replaced by a barrier with locks when the appropriate threshold is reached.

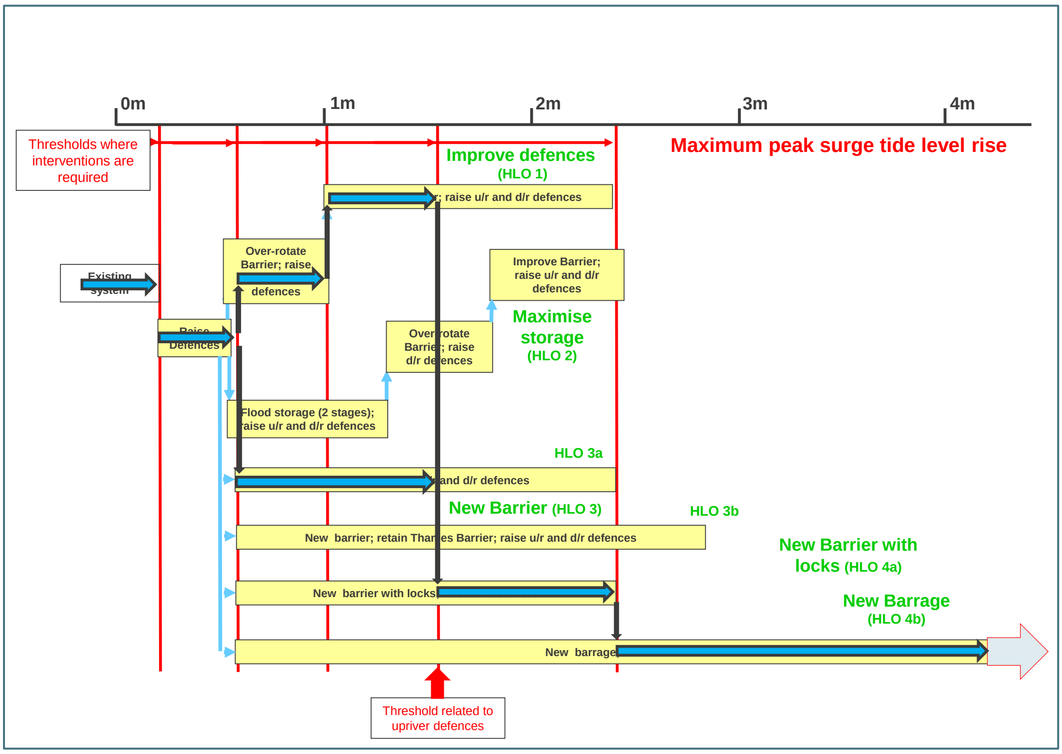

Figure 7 The preferred High Level Options for tidal flood management

3.11 MONITORING

The TE2100 Plan includes monitoring of indicators of change in order to identify the actual changes that occur. These include mean sea level, high tide level, peak surge tide level, river flood flows and updates in government guidance on the climate change allowances to be used in flood risk management (HR Wallingford 2011). The results will be used to periodically update the Plan including the dates when interventions are required.

4 IMPLEMENTATION OF THE TE2100 PLAN

4.1 UPDATING THE PLAN

After completion of the TE2100 Plan, implementation of the activities described in the Plan commenced. In addition, the following steps are being taken to update the Plan:

1. In order to monitor the evolution of the TE2100 Plan, ten indicators of change were identified which are monitored on a regular basis so that the Plan can be updated regularly.
2. For each indicator, the thresholds where responses will be needed to maintain the required level of flood risk were identified.
3. The lead time for planning and constructing each portfolio of responses was estimated in order to determine the length of time before the responses are needed when decisions should be taken (the 'lead time'). The time when a decision must be made is referred to as a 'decision point'. Figure 8 shows the concept of lead times and decision points.

4. The TE2100 plan included assumed dates when the responses will be required, and assumed dates when decisions must be made.
5. The indicators are monitored. The monitoring results are used to update the estimated dates when portfolios of responses must be implemented, and the dates when decisions must be made.
6. The timing of a decision to implement an intervention is based on:
   a. The rate of change of the indicator (which is unlikely to be linear).
   b. The threshold value when an intervention is required.
   c. An estimate of how the indicator will continue to change, in order to estimate the date when it reaches the threshold value.
   d. The lead time for planning and constructing the intervention.

   The process is illustrated in Figure 9. Figure 9 shows the effect of faster and slower rates of change compared with the TE2100 Plan. Faster rates of change bring forward decisions, and slower rates of change delay decisions.
7. The TE2100 Plan was reviewed in 2016 and will continue to be reviewed every five years. If the estimated dates when thresholds will be reached and decisions must be taken change, the Plan will be updated.
8. The general approach to updating the Plan will be to change the dates of the interventions but not the interventions themselves.
9. However if very significant changes occur in the expected dates when thresholds will be reached, the choice of options will be reviewed. This is because an alternative option may be more effective for managing flood risk under the changed circumstances. Alternative options were included in the TE2100 plan.
10. The preferred options and the alternative options will be re-appraised, using the updated best estimates of future change. This could lead to a change in the selected option. For this reason, responses should be as adaptable as possible to avoid undertaking work that may not be needed in the future.

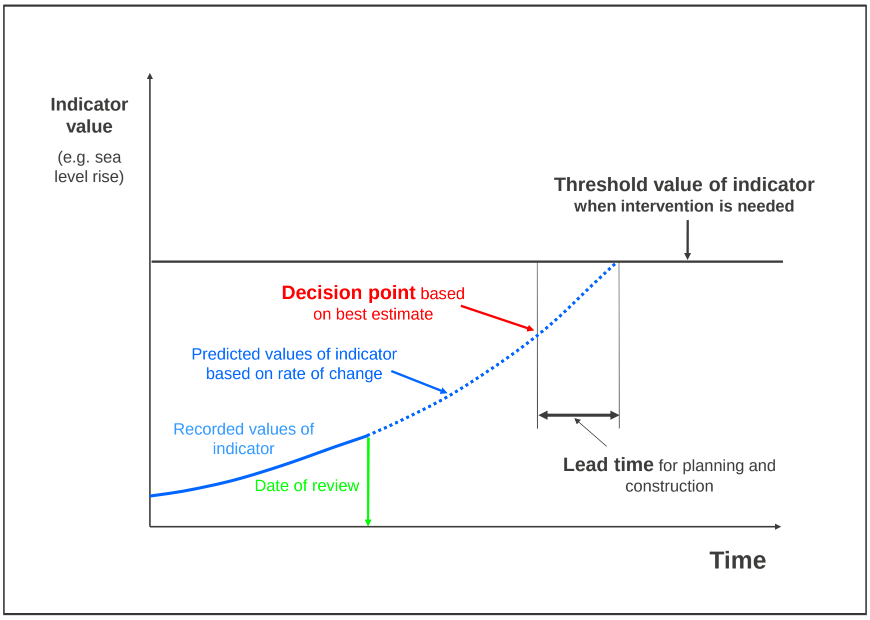

Figure 8 Lead time and decision point for implementing an intervention

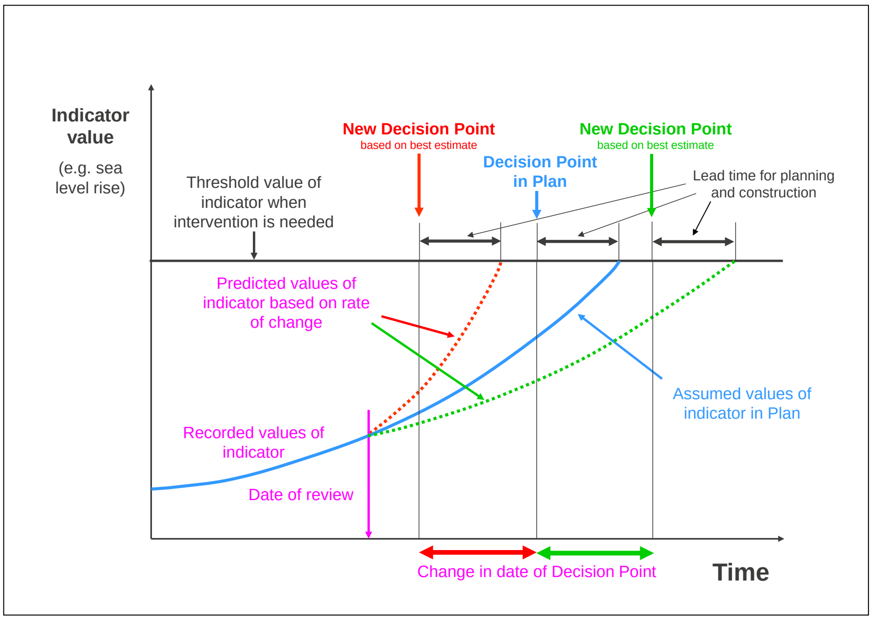

Figure 9 Impact of different rates of change on decision point

The preferred options and the alternatives all involve a similar approach until a critical water level threshold is reached at the Thames Barrier. At this stage a major change to the system will be needed. The critical drivers for this are mean sea level and peak surge tide level, and the current assumed date for major interventions is 2070 based on the climate change scenarios developed by the British Government in 2006 (Defra 2006).

The key indicators of change are:

Indicator 1 – Mean Sea Level relative to land level

Indicator 2 - Peak surge level relative to Mean Sea Level, which is the maximum water level which occurs as a result of tidal surges

Indicator 3 - Peak river flows

Indicator 4 - Condition of flood defence assets

Indicator 5 – Operation of the Thames Barrier and other barriers

Indicator 6 - Development including the numbers of people and properties in the floodplain

Indicator 7 - Erosion and deposition

Indicator 8 - Habitat areas and quality. The TE2100 Plan includes the creation of 1,200 ha of intertidal habitat over the lifetime of the Plan

Indicator 9 - Land use planning and development activities

Indicator 10 - Public/institutional attitudes to flood risk

4.2 PROGRESS TO DATE

Implementation of the TE2100 Plan commenced in 2012. A single organisation, TEAM2100, was appointed consisting of a combined team of a consultant (CH2M) and Environment Agency staff. TEAM2100 has a 10-year contract to refurbish, improve and replace tidal flood defences on the Thames estuary including the Thames Barrier and other flood control barriers.

The first review of the TE2100 Plan was completed in 2016 (Environment Agency 2016). At this early stage changes were in line with the expectations of the Plan and there was no need to modify either the content or the timing of intervention measures.

The indicators of change were reviewed and the findings included the following:

- Sea level rise and changes in land levels are causing an increase in sea level relative to the land of 4.5 mm/year, slightly higher than the rate projected in the plan (Indicator 1).
- There was no discernible trend in either surge tide levels relative to Mean Sea Level (Indicator 2), the peak river flows (Indicator 3) or the number of times the Thames Barrier was closed for surge tide events (Indicator 5).
- New guidance on climate change scenarios has been introduced which would change the dates of the interventions. However it was decided not to change the Plan at this early stage: the rate of sea level rise is in line with the Plan and the decision points for most of the interventions are several years into the future.
- An ongoing maintenance and repair programme for the flood defences had been implemented based on regular condition inspections and tests as required (Indicator 4).
- The number of properties in the tidal Thames floodplains has increased by about 4% (Indicator 6). New developments have taken account of the requirements of the TE2100 Plan including the major London Gateway Port (Figure 10), where the quay level has been raised to a future flood defence level consistent with the Plan.

Figure 10 London Gateway Port in the lower estuary

- Erosion in front of the defences is an ongoing problem on the estuary as it reduces structure safety factors. The asset management programme includes identification of erosion and deposition (Indicator 7).
- The Plan indicates that compensation intertidal habitat is needed immediately. However a system for monitoring intertidal habitat area has not been established and difficulties had been encountered obtaining suitable sites (Indicator 8).
- The indicators for Development (Indicator 9) and attitudes to flooding on the estuary (Indicator 10) had not been developed when the 2016 review was carried out.

4.3 STANDING THE TEST OF TIME

At this early stage in the implementation of the Plan, the projections of change are consistent with the original Plan and new works (including flood defences, port facilities and other developments) are being implemented in accordance with the Plan. Some of the key success factors are considered to be:

- Understanding the estuary: major data collection programmes and studies were carried out to develop an in-depth understanding of estuary processes and the key flood defence data needed to design the Plan, including defence crest levels, key dimensions and defence types. Whilst this required a major investment, it provides the base data needed for flood management on the estuary.
- The wide range of options considered together with detailed feasibility studies, to ensure that the selected options are feasible and the most appropriate taking account of technical, economic, environmental and social criteria.
- Clear communication of the outcomes of the Plan including the TE2100 Plan (essentially a list of actions needed to undertake the Plan) and documents giving details of the works required, flood defence crest levels, etc.
- Long term view. The options cover sea level rise in excess of 4 metres. It has therefore been possible to plan no-regrets interventions that are consistent with the long-term vision.

The TE2100 Plan is relatively new and has not been fully tested. There are however a number of aspects of the Plan that have been shown by experience to require improvement, including the following:

1. Agreement on availability of land: whilst a land strategy was developed for the TE2100 Plan, there is a need to ensure that land would be made available when required. This has already been difficulty obtaining areas for new intertidal habitat, where the flood defences would be breached and/or realigned.
2. Agreement on riverside strategies: the TE2100 Plan envisaged that the flood defence improvements would form part of a landscape strategy for the riverside in collaboration with planning authorities and other local partners. However the partnership working to achieve this aspiration has not taken place.
3. Integration of all sources of flooding: tidal flood risk and fluvial flood risk on the Thames have been examined in detail. In addition, studies on other sources of flooding have been carried out including surface water and ground water. However the results have not been fully 'joined up'. In particular, the TE2100 Plan has not been fully linked with drainage plans for the defended areas.
4. The detailed data produced in the TE2100 has not been fully integrated with existing data sets, in particular the Environment Agency's database on flood defence assets. As a result, the Environment Agency's database does not contain the best available data.

5 KEY POINTS FOR APPLYING THE APPROACH IN OTHER AREAS

The approach to adaptation adopted in the TE2100 Plan for multi-hazard situations could theoretically be applied in other locations exposed to climate change, natural hazards or other variable environmental or social factors.

This should begin with sufficient flood risk assessment to understand what scale of flood management interventions can be justified as the climate changes and other hazards occur.

In New Zealand, the implications of climate change are the same, albeit at possibly different rates of change in sea level rise (for low-lying coastal environments) and weather events. In addition, New Zealand is posed with significant natural hazard risks including tsunami, earthquake and land instability, particularly following large earthquakes. Consideration must therefore also be given to the potential effects of these natural hazards on the flood management solutions being considered, so that any adverse effects are understood and accounted for in either the design, cost or expected performance of the flood management solution.

By way of example, if a flood stop bank were to be considered on land susceptible to settlement or lateral spread in an earthquake, then the multi-hazard assessment should identify the probability and impact of this risk on the proposed solution (reduced design standards of protection, damage needing repair, etc.) and the solution should be adapted to include mitigation measures and associated cost or risk cost applied when compared against other options.

This additional natural hazard risk exposure within New Zealand places an even greater reliance on consideration of adaptable pathways for flood management solutions, particularly as the effects of other hazards could be of similar magnitude to sea level rise yet could occur at any time and in doing so, could bring forward the decision point by decades and expose communities to a higher level of risk for extended periods of time.

The Christchurch earthquake series have demonstrated many examples of significant impact on land drainage infrastructure. In the Dudley Creek catchment, land settlement plus lateral spread plus deposition in-stream of expressed liquefaction, significantly reduced the flood conveyance capacity of Dudley Creek. When coupled with two wet years, flooding occurred on several occasions, with significant flooding of houses above floor level. In response a flood management solution has been fast tracked at a net cost in the order of $50M, an expense that otherwise may not have been required for some time if at all. Despite the upgrade project, this catchment and project remain at risk of future earthquakes and associated damage.

This uncertainty of timing of a natural hazard event introduces further complexity into how flood risk is assessed and responses considered, yet the potential scale of impact of a natural hazard event means that consideration of natural hazards cannot be ignored. This however will lead to flood management solutions that have lower exposure to multi-hazard risk and are more adaptable.

In order to develop a plan for adaptation, the following questions should be addressed:

1. What are the main hazards and how are they likely to change and/or manifest? These include flooding from rainfall, rivers, groundwater and surge tides together with tsunami and earthquake.

   Whilst sea level rise is a gradual change with time to observe and adjust, the likelihood of a tsunami or earthquake is much more difficult to assess and the effects are immediate, without time to adjust. Where there is doubt, a precautionary approach is recommended where it is assumed that these hazards could occur at any time.

2. What impacts could the hazards have, both now and in the future?
3. Which areas will be affected by each of the hazards? Are there areas that could be affected by several hazards?
4. What future scenarios should be used in planning?
5. What are the thresholds where interventions will be needed?
6. What threshold values should be used for design (for example, critical water levels at particular locations)?
7. What are the limits of adaptation (i.e. the maximum amount of adaptation before a different strategy is needed)?

8. What are the available adaptation options? Are there options that can provide protection against more than one threat? Are the options viable? Is retreat from some areas an acceptable option?
9. What sequence of adaptation actions should be followed?
10. What are the constraints on existing infrastructure, for example condition?
11. What indicators should be used to monitor and update the adaptation plan?

An important element of the analysis is to understand the relative importance of each hazard, how they combine together and which areas are most affected. In TE2100 the hazards were investigated in order of severity to provide an overall assessment of the impacts of each hazard. The hazards were then combined to achieve an integrated plan.

A particular aspect of adaptation in the face of natural hazards is whether retreat from some areas is the best long-term option. On the Thames estuary, protection of some of the lower estuary floodplains is not economically viable and managed realignment is the preferred option, where the flood defences are breached and the land is used for intertidal habitat creation to fulfil environmental objectives. In New Zealand and elsewhere there are some areas where the threat from floods and other hazards is so severe that retreat becomes a realistic option.

In view of the difficulties of retreat in developed areas that include private properties, retreat might become a medium or long-term goal where development is gradually moved as the opportunities arise. There is of course the risk that a severe hazard could occur during this transition period and measures to reduce the consequences of the hazard during this period may be required.

Examples where development has been relocated to reduce flood risk include the Mississippi floodplains following the 1993 floods and the Room for the River project in the Netherlands, which involves widening the river corridor to reduce flood levels and therefore flood risk.

6 CONCLUSIONS

1. The TE2100 Plan includes a method for adapting a flood defence system for a changing climate.
2. The main hazards on the Thames estuary in order of importance are flooding from: the sea, the River Thames (fluvial flooding), rainfall, tributaries of the River Thames; groundwater.
3. The adaptation method could theoretically be applied in any situation.
4. The adaptation method requires an understanding of the potential long-term impacts of change so that a no-regrets adaptation plan can be developed that is regularly monitored and updated.
5. Adaptive planning is even more crucial in New Zealand due to the overlay of natural hazard risks.

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