

Evaluation of Flexibility in Adaptation Projects for Climate Change

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Research Article

Keywords: Evaluation of flexibility, adaptation projects, climate change, uncertainty, people, analytical tool, long- term adaptation

Posted Date: September 14th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-865253/v1>

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Version of Record: A version of this preprint was published at Climatic Change on March 1st, 2022. See the published version at <https://doi.org/10.1007/s10584-022-03331-0>.

1 Evaluation of flexibility in adaptation projects for climate change

2 Abstract

3 Climate change adaptation inherently entails investment decision-making under the high levels of uncertainty.
4 Under these circumstances, the option of deferring a decision to adapt is one of possible strategies to address
5 uncertainty. However, this decision will potentially leave people and areas exposed to the risk of coastal
6 flooding during the deferral. In order to address this issue, a single fixed large investment can be divided into
7 two or more sequential investments. This reduces the initial investment cost and adds flexibility about the size
8 and timing of subsequent investment decisions as the magnitude of climate change becomes more available.
9 This paper employs a real option analysis framework, as an analytical tool, to evaluate adaptations including
10 flexibility to reduce both the risk and uncertainty of climate change, against increasing coastal flooding due to
11 sea-level rise as an example. This paper considers (i) how to design the sequence of adaptation options under the
12 growing risk of sea-level rise, and (ii) how to make the efficient use of flexibility included in adaptations for
13 addressing uncertainty. This research incorporates a set of flexibilities (i.e. wait or future growth) into single-
14 stage investments (i.e. raising coastal defence from 2.5 mAOD to 3.5mAOD or 4.0 mAOD) in two or three
15 stages so that a set of multiple-stage adaptations are created to address both the risk and uncertainty of climate
16 change. The proposed method compares the multiple-stage adaptations in economic terms, including
17 optimisation, providing important additional information on the efficiency of flexible adaptation strategies given
18 the uncertainty of climate change. The results from the analysis suggest that an efficient and robust strategy can
19 be chosen for a short- and long- term adaptation.

20 1. Introduction

21 Climate change adaptation inherently entails investment decision-making under the high levels of uncertainty
22 (Dawson et al., 2018). Under these circumstances, deferring a decision is one of possible strategies to increase
23 the value of such investments. (Dixit and Pynidick, 1994; Kim et al., 2018). It enables decision-makers to learn
24 the future, thus, informing decisions. However, such decisions will leave people and areas exposed to the risk of
25 coastal flooding during learning. In order to address this issue, a single large investment can be divided into two
26 or more sequential investments (Hallegatte, 2009; Haasnoot et al., 2013; Woodward et al., 2014). This decision
27 helps reduce the initial investment cost and, thus, leads to immediate actions to cope with the risk of flooding.

1 This type of adaptation approach has been previously referred to as diverse terms such as ‘adaptation pathways
2 approach (Ranger et al., 2013; Nicholls et al., 2014)’, ‘dynamic adaptation (Hallegatte, 2009; Haasnoot et
3 al., 2013)’ or ‘real options approach (Neufville, 2003; Woodward et al., 2014)’. Such strategies seem to be
4 robust against the future uncertainty because the remaining adaptations, after the first adaptation is implemented,
5 provides an opportunity to observe and learn, thus modifying the decisions in response to the unfold future
6 (Hallegatte, 2009; Haasnoot et al., 2013).

7

8 Theoretical background of real options analysis is based on the fact that flexibility given to decision-makers is the
9 right, but not the obligation (Dixit and Pindyck, 1994; Park, 2002; De Neufville, 2003). In the context of climate
10 change adaptation, flexibility in adaptation takes various forms such as deferring the upgrade of flood defence,
11 buying a wider land for future upgrade or growing flood defence in the future. As the coastal adaptation requires
12 a large investment cost, flood risk analysts or decision-makers are left in the face of challenging tough decisions
13 on the investment. Real options analysis is an assessment tool to value flexibilities included in investment
14 options (Dixit and Pindyck, 1994). This is widely used to address the uncertainty of future market states (e.g. the
15 price of product or stock) in finance. This concept is now vigorously used in climate change realms where
16 uncertainty is deep and everywhere. A way to exercise the right (i.e. flexibility) in climate change adaptation has
17 an effect on reduction in the risk of climate change and, subsequently, the value of adaptation options under
18 various climate change scenarios (Linquiti and Vonortas, 2012; Woodward et al., 2014). Flexibility can occur in
19 coastal adaptations with diverse forms: (1) wait, (2) future growth or (3) both. The inclusion of such flexibilities
20 in coastal adaptations enables decision-makers to invest by stages.

21 This type of coastal adaptation (hereafter, referred to as multiple-stage adaptation) has some advantages in
22 addressing both risk and uncertainty. Firstly, it provides a high degree of freedom in making investment
23 decisions under uncertain future states (Dixit and Pindyck, 1994). As long as the flexibility is alive in the
24 remaining options, there is a choice either to invest or to wait for option holders at a given time (Bellman, 1952).
25 Secondly, the multiple-stage adaptation can part investment costs in stages as planned so that it can facilitate an
26 initial action at a relatively low cost. In addition, if the remaining option is proved to be unnecessary in the
27 future, we can drop it and save the due cost in the future. Lastly, the multiple-stage adaptation enables us to
28 adjust actions or plans in response to the future states (Linquiti and Vonortas, 2012). After an investment in a

1 costly infrastructure is made, it will be difficult to adjust its capacity and size in response to unexpected
2 conditions (e.g. sea-level rise, future growth rates, etc.). However, if the costly infrastructure is engineered to be
3 built in multiple stages, it enables us to take adjustable actions in response the future.

4

5 Despite such advantages, the multiple-stage adaptation requires an additional expenditure to incorporate
6 flexibility (i.e. future extension) into its design or planning (Dobes, 2010; Woodward et al., 2014). For example,
7 the design of extendable coastal defence may require a wider area of land and/or stronger foundation than
8 without a future extension (Dobes, 2010). In addition, each investment cycle also requires mobilisation costs.
9 Thus, the inclusion of flexibility into an originally non-flexible option leads to increase in its overall cost by
10 separations. The previous studies have also assessed adjustable adaptation options that include the flexibility of
11 future extension in comparison to a baseline adaptation option (without flexibility). Most studies regarding real
12 options suggest that an adjustable adaptation option in the future is a more robust strategy under the uncertainty
13 of climate change (Dobes, 2010; Linqiti and Vonortas, 2012; Woodward et at., 2014; Hino and Hall, 2017).

14 In the literature of decision-making, real options analysis is frequently compared to robust decision making in
15 that both approaches provide robust adaptation options which perform well across a variety of futures (Dittrich
16 et al., 2020). Robust decision-making is intended to find an optimal trade-off between decrease in the expected
17 performance and increase in the performance in the worst case, while real options analysis is to evaluate
18 flexibility that increases the robustness of the adaptation options. Both approaches have much in common in
19 dealing with uncertainty. The considered adaptation options with flexibility are quantitatively assessed in order
20 to pursue optimality or balance between the intended performance and the unacceptable risk under uncertainty
21 (McInerney et al., 2009; Wreford et al., 2020). Both approaches mostly suggest that the success of adaptation
22 strategies depends on how to incorporate flexibility into the adaptation strategies at the minimum loss of their
23 expected performance (McInerney et al., 2012).

24 There are diverse ways in which adaptation strategies are quantitatively assessed across all the possible future
25 states. Some studies have shown how to demonstrate the economic efficiency of flexible adaptations under the
26 combination of socio-economy changes and climatic changes (Hino and Hall, 2017; Manocha and Babovic,
27 2017). Real options analysis combined with Multi-Criteria Decision Analysis (MCDA) includes qualitative
28 drivers (e.g. adaptive capacity, information accessibility, decision-making process, etc.) in option evaluation

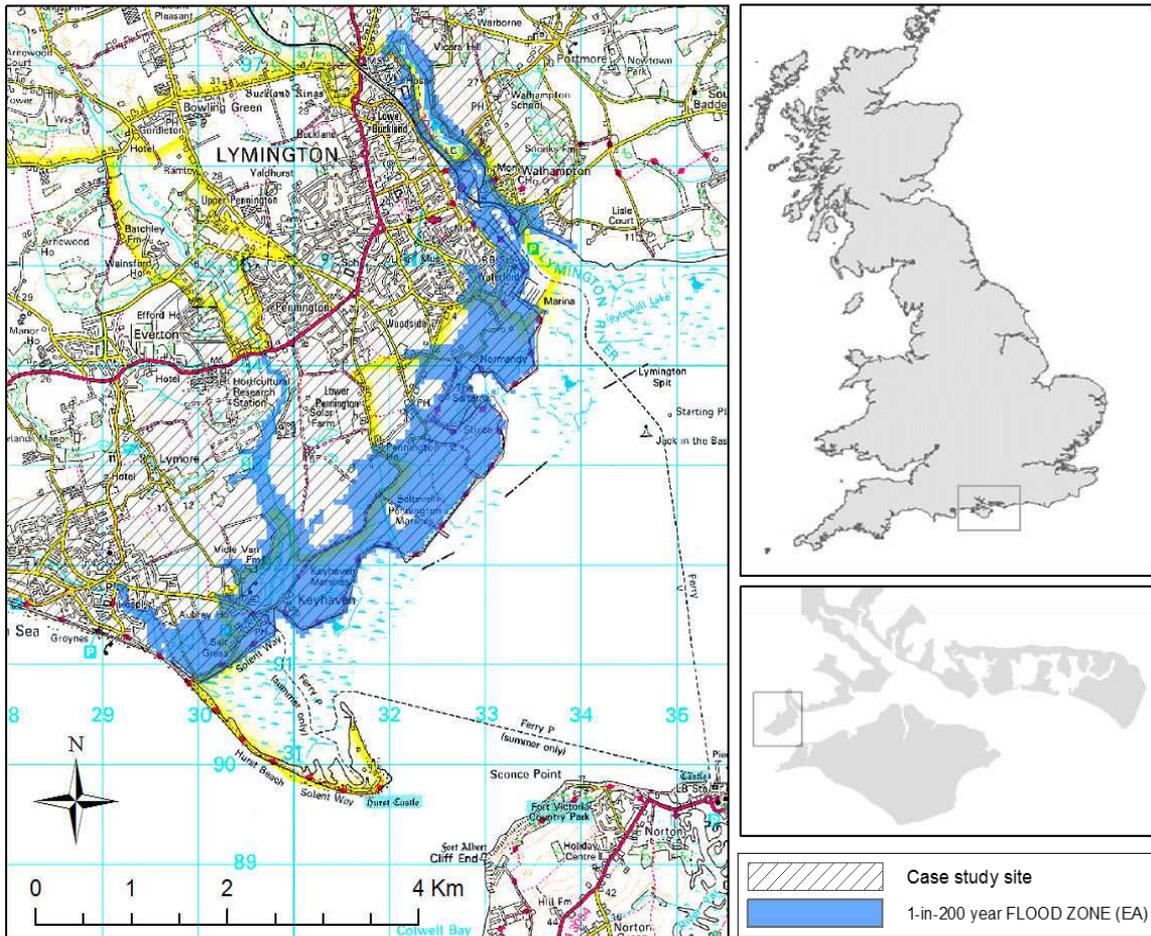
1 framework so as to stimulate the long-term actions against climate change (Lawrence et al., 2019). Some studies
2 focus on structuring the process of designing climate adaptation policies that can flexibly respond to the unfold
3 futures (Buurman and Babovic, 2016). A portfolio of coastal adaptation paths which grow in response to the
4 possible future states are evaluated by NPV (net present value) method (Liquiti and Vonortas, 2012;
5 Woodward et al., 2014). The net present values of each adaptation path under probability-weighted future states
6 are aggregated to demonstrate whether a set of adaptation paths are worth investing and which one is more
7 preferable in the perspective of economy efficiency. The investment timing in regard to the flexibility of wait
8 has been investigated to maximise the economy efficiency of coastal adaptations under diverse sea-level rise
9 scenarios (Kim et al., 2018). Most studies on real options analysis suggest that, rather than non-flexible
10 adaptations, incremental and adjustable approaches to the upgrade of infrastructure are more economically
11 efficient for the long-lasting infrastructure (Manocha and Babovic, 2017; Smet et al., 2017).

12 There are also some limitations of real options analysis in application to climate change adaptation. Firstly, the
13 evaluation of real options requires a very complicated process. All the uncertainties relevant to decision-making
14 are recognized and integrated in option evaluation process (Kind et al., 2018). Secondly, the option evaluation
15 needs the probabilities of the future states based on subjective choices and expected judgment (Kwakkel, 2020).
16 Thus, the results from real options analysis seem to be subjective depending on the preference of decision-
17 makers (i.e. flood risk, cost or benefit). Thirdly, a baseline option is needed to illuminate the optimality of
18 flexible or adjustable adaptation in real options-based framework. It is ambiguous whether flexibility is efficient
19 or worth investing under uncertainty. These limitations should be explicitly explained to vigorously apply real
20 options analysis to climate change adaptation, in particular, irreversible investments under uncertainty.

21 The contribution of this paper is to provide a comparative process to assess the multiple-stage adaptations or
22 adaptation paths in a quantitative way that the optimisation of the adaptation strategies is made to maximise the
23 value of flexibility under uncertainty. However, the evaluation of multiple-stage adaptations causes some
24 practical issues: (1) the timing of exercising each stage adaptation and (2) the size of each stage adaptation. With
25 focus on these issues, this paper addresses questions on how to design the sequence of adaptation options under
26 the risk of coastal flooding and sea-level rise, how to evaluate such flexible adaptations and how to make the
27 most efficient use of flexibility included in adaptation options. In this regard, this paper takes different
28 approaches to the application of real options analysis in climate change adaptation. Firstly, we view the
29 flexibility of wait as an important factor to make investment decisions for an adaptation option. The investment

1 decision can be deferred to any time in the future. Thus, more information will be available for learning and
2 adapting to the future. Upon this condition, the maximum value of an adaptation option and its investment
3 timing can be assessed by applying real options framework to each stage of adaptation. Secondly, multiple-stage
4 adaptations are quantified for comparisons to single-stage adaptations. In order to compare between the
5 flexibilities of wait and growth, single-stage adaptation options are divided into two- or three- stage adaptation
6 options. The single-stage adaptations can be used as baseline adaptations for comparison to the equivalent
7 multiple-stage adaptations. This shows how efficient the flexibilities included in coastal adaptations are under
8 uncertain conditions. Lastly, this research assesses multiple- and single- stage adaptations for all the possible
9 SLR scenarios and observe how the economy efficiencies of the considered adaptations change over SLR
10 scenarios. This implies that this assessment eliminates subjective views or judgements towards the uncertain
11 futures. Thus, this research considers each SLR scenario as future uncertainty with a premise that the
12 uncertainty of sea-level rise will be reduced by the future generation's decisions based on learning and
13 observing.

14 This paper uses the past UKCP 09 data (UK climate projection 09) because this research had been conducted
15 when only the UKCP09 was available (Lowe et al., 2009). Now these dataset have been upgraded as UKCP 18.
16 Lymington is chosen as a vulnerable area to coastal flooding and sea-level rise (Ruocco et al., 2011; Wadey et
17 al., 2012), and the coastal flood adaptation has been planned to improve the capacity of the current coastal
18 defence against the risk of coastal flooding. The present and future flood risks and the corresponding adaptation
19 measures (a single-stage adaptation) have been well-understood by the previous studies (Wadey et al., 2013).
20 Thus, the results from the analysis enable us to make the efficient use of flexibility of wait and growth under the
21 uncertainty and risk of sea-level rise. This analysis finally provides a way for decision-makers to choose a
22 flexible and robust adaptation in terms of economy efficiency under given conditions (e.g. types of coastal
23 adaptations, adaptation costs, the uncertainty of SLR scenarios, the risk of coastal flooding, etc.).



1

2 **Figure 1.** The case study site of Lymington with a 1-in-200 year flood risk zone indicated by Environment
 3 Agent (UK) from OS maps

4

5 This paper consists of four sections. The next section explains the overall framework to value multiple-stage
 6 adaptation options. In the following section, we provide results from the evaluations of all the possible
 7 adaptation paths with changes to costs for flexibility under each SLR scenario. For more information, the
 8 detailed analysis on the option evaluation has been included in supplementary documents (1, 2 and 3). The
 9 quantitative comparisons of the adaptation pathways are undertaken to provide economically efficient strategies
 10 under the uncertainty of SLR scenarios. Finally, this paper discusses the results and its implications for climate
 11 change adaptation.

12

1

2 **2. Framework to assess multiple-stage adaptations with flexibility**

3 **2.1 Evaluation of deferrable adaptation options and growth adaptation option**

4 If an adaptation option is deferrable, two values exist (Dixit and Pyndick, 1994). A value for wait is called a
5 continuation value, while a value for investment is a termination value (Bellman, 1952; Dixit and Pindyck, 1994;
6 Yang et al., 2007; Kim et al., 2018). A higher one of both values in any given year t is an option value at that
7 time defined by equation (1).

$$F_t = \max[F_{con,t}, F_{ex,t}] \quad (1)$$

8 Here, $F_{con,t}$ is a continuation value in year t , $F_{ex,t}$ is a termination value in year t and F_t is an option value in the
9 year t , which is the higher one of the two values. If a continuation value ($F_{con,t}$) is greater than a termination
10 value ($F_{ex,t}$), it suggests that waiting is preferable to investing and vice versa (Bellman, 1952). The termination
11 value in year t is an option value when the investment is made at year t . Thus, it can be defined by equation (2).

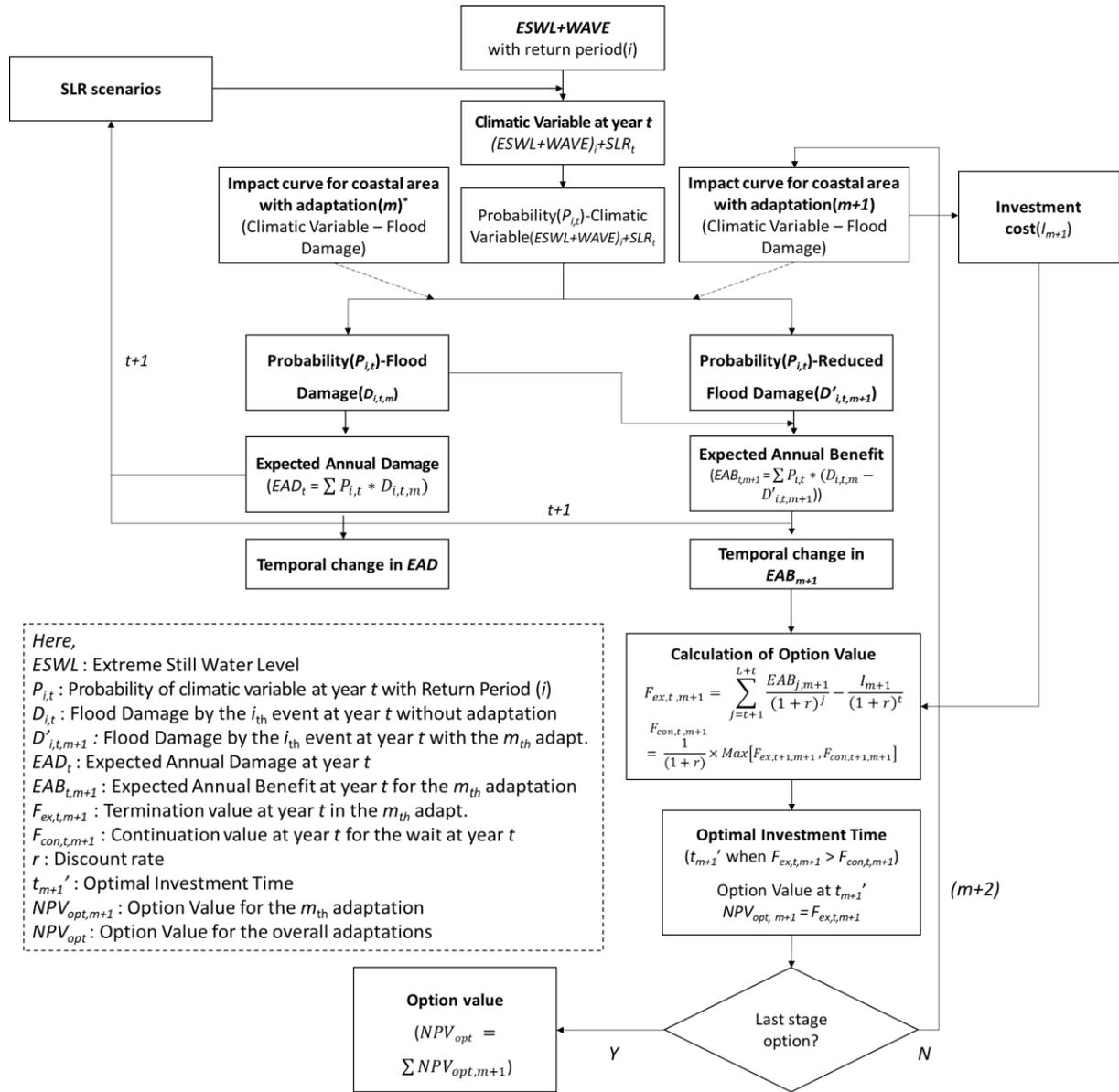
$$F_{ex,t} = \sum_{i=t+1}^{L+t} \frac{EAB_i}{(1+r)^i} - \frac{I}{(1+r)^t} \quad (2)$$

12 Here, EAB_i is the expected annual benefit of a project with the investment cost of I at year i , r is discount rate
13 and L is the project life (= 100 years). A continuation value ($F_{con,t}$) at year t is the higher one of continuation and
14 termination values at year $t+1$ discounted by a discounting factor $1/(1+r)$. Thus, a continuation value is defined
15 by equation (3).

$$F_{con,t} = \frac{1}{(1+r)} \times \max[F_{ex,t+1}, F_{con,t+1}] \quad (3)$$

16 These two equations (i.e. $F_{ex,t}$, $F_{con,t}$) can determine whether to defer or to invest at any year. The calculation of a
17 continuation and a termination value starts from the end year of sea-level rise (SLR) projection by a backward
18 induction method (Kim et al., 2018).

19 This evaluation process can be extended to a multiple-stage adaptation by estimating the option value and
20 optimal investment time for each stage of a multiple-stage adaptation option as shown in Figure 2. For option
21 evaluation, this analysis adopts the national discount rates (r) from the Green Book (HM Treasury, 2003) (i.e.
22 3.5% for the first 30 years, 3.0% for the next 45 years and 2.5% afterwards).

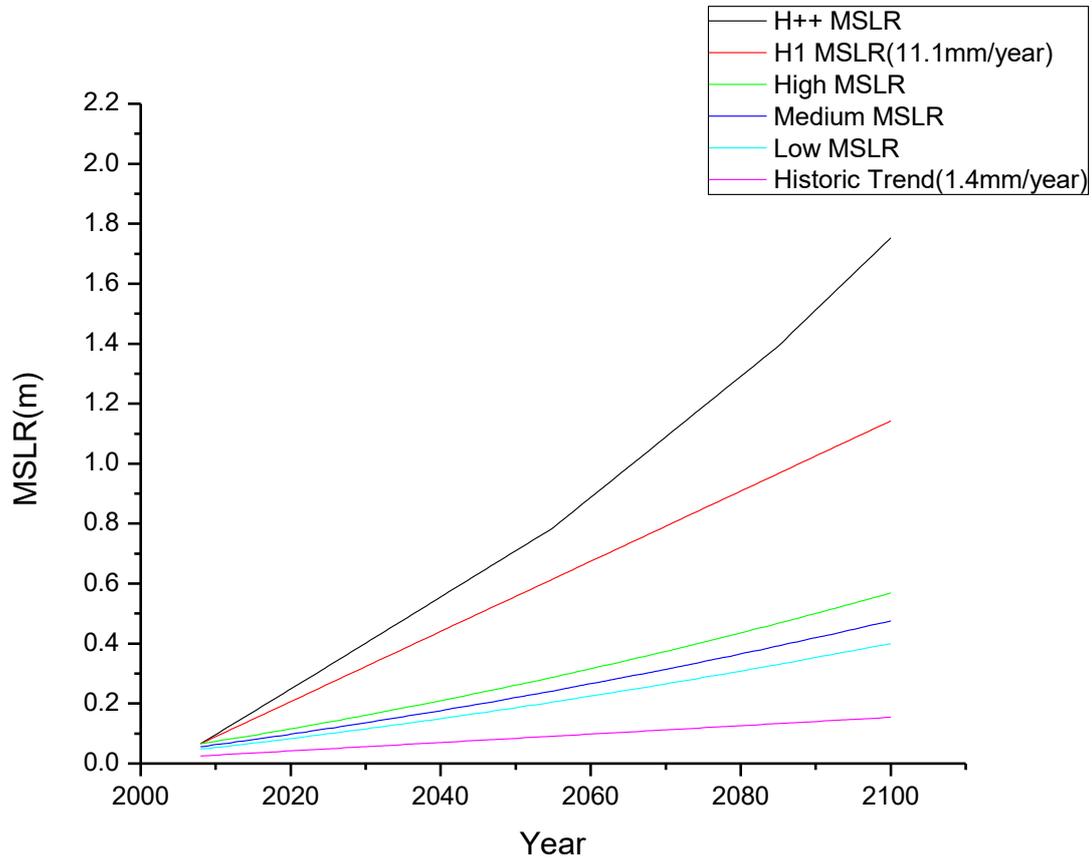


* Note: the impact curve of the m_{th} adaptation should be replaced by that of the $m+1_{th}$ adaptation for the next calculation

Figure 2. The framework of option evaluations for multiple-stage adaptations

Reduction in flood damage by any adaptation measure is benefit that decision-makers expect to gain from the investment. This study evaluates Expected Annual Benefit (EAB) at a given year - the performance of an adaptation measure - which depends on sea-level rise and ways to upgrade coastal defence in an area of interest. To estimate changes in EAB for any adaptation measure across sea-level rise, a pair of impact curves for the initial and upgraded defence conditions have been chosen. The changes in EAB across sea-level rise for any

1 adaptation measure show the unique response of the coastal area to sea-level rise. The case study area considers
 2 six SLR scenarios in which we will evaluate temporal changes in the annual performance of each adaptation
 3 measure (Refer to Supplement 1 for the estimation of EAB). The trajectories of sea-level rise by different
 4 scenarios for Lyminster are drawn during the 21st century in Figure 3.



5
 6 **Figure 3.** Mean sea-level rise (relative to 1990) scenarios for Lyminster: 2008 to 2100 (Lowe et al., 2009) - the
 7 H++ MSLR is derived from the global scale sea-level rise data (Nicholls et al., 2014) by scaling-techniques and
 8 the historical trend of sea-level rise (1.4 mm/year) is from the Southampton tidal gauge (Haigh et al., 2009).

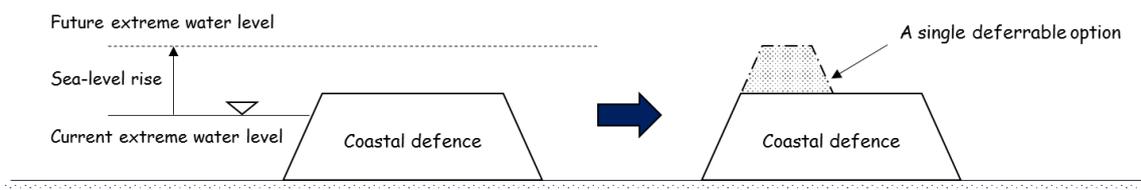
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10 2.2 Description of terms of single- and multiple-stage adaptations

11 A single-stage investment has been transformed into multiple-stage sequential investments so that the possible
 12 sets of the adaptation pathways are conceptualised in Figure 4. 0.5m or 1m increase is considered for coastal
 13 defence upgrade against the rising sea-level in Lyminster. The current crest level of the coastal defence is
 14 around 2.5 meter Above Ordnance Datum – which is, hereafter, termed mAOD. The coastal defence can be

1 raised to 3.0, 3.5 or 4.0 mAOD in one or more stages. This paper denotes $U_{i \rightarrow j}$ to an adaptation measure of
 2 raising the crest of coastal defence from the initial height (i) to the upgraded height (j). This terminology also
 3 represents adaptation pathways by putting terms together. For example, a two-stage defence upgrade from the
 4 current level - it is termed (c) in the paper - through 3.0 mAOD to 3.5 mAOD is denoted by $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m}$.

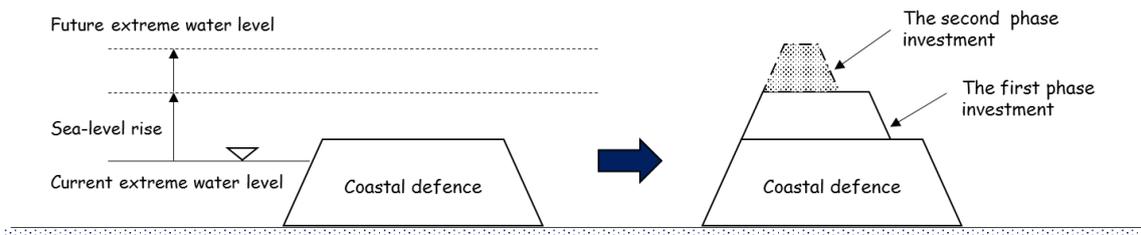
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7

(a) Option to wait

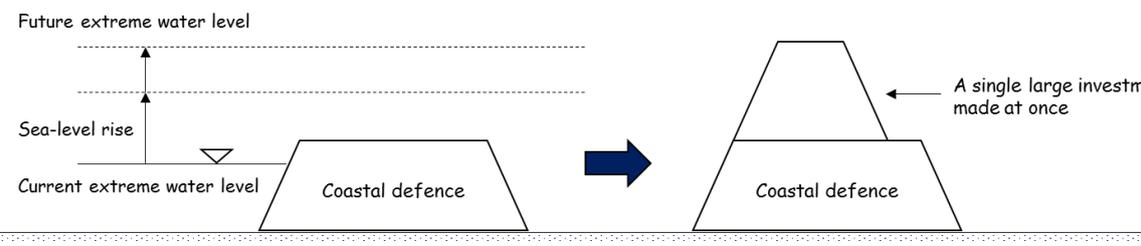
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(b) Option to grow

10



11

(c) Option to invest now

12

13

14 **Figure 4.** Examples of real options for the case of coastal defences: (a) Option to wait; (b) Option to grow; and
 15 (c) Option to invest now – The coastal defences have been upgraded according to sea-level rise - The dash-lined
 16 coastal defence is the upgrade scheme whereas the solid-lined coastal defence means the upgraded defence.

17

18

19

1 2.3 Estimation of costs of multiple-stage adaptations

2 The additional costs should be paid for including flexibility in adaptation options. If not, adaptation options with
3 flexibility would be always more preferable than non-flexible one. It is because the future uncertainty will be
4 addressed with the high degree of freedoms induced by the flexibility at no cost. Thus, real options analysis
5 assumes for the practical and theoretical reasons that the flexibility should be priced (Pindix and Dixit, 1994).
6 The division of a single investment into two sequential investments increases the overall investment cost as
7 shown in equation (4) and (5).

8

9

$$\begin{aligned} I_o + I_f &= (I_{o,1} + I_{o,2}) + \left(\frac{1}{2}I_f + \frac{1}{2}I_f\right) \\ &= (I_{o,1} + \frac{1}{2}I_f) + (I_{o,2} + \frac{1}{2}I_f) \end{aligned} \tag{4}$$

$$I_1 = I_{o,1} + \frac{1}{2}I_f, \quad I_2 = I_{o,2} + \frac{1}{2}I_f \tag{5}$$

10 Here, I_o is the cost of a single-stage adaptation; I_f is the cost of flexibility; $I_{o,1}$ and $I_{o,2}$ are the net costs of the
11 first- and the second- stage adaptations – both of which are made by dividing a single-stage adaptation into
12 sequential adaptations; I_1 and I_2 are the investment costs of the first- and the second- stage adaptation,
13 respectively. For simplicity, it is assumed that the cost of flexibility is evenly distributed to each stage (i.e.
14 $I_f = \frac{1}{2}I_f + \frac{1}{2}I_f$). The investment cost of upgrading coastal defence (i.e. impermeable revetments and seawalls)
15 is set to be £ 64.2 million, which is an indicative cost for upgrading 15km-long coastal defence up to 3.5 mAOD
16 level (NFDC, 2010). The estimation of the costs for different heightening follows a linear relation by the
17 previous study (Jonkman et al., 2013) and these distribution rules (Eq (4) and (5)) are applied for each stage
18 adaptation. The investment cost for each adaptation is explained in Supplement 2.

19 3. Economy efficiency of coastal adaptations under uncertainty

20 3.1 Quantifications of single- and multiple- stage adaptations

21 At the early stage of planning coastal adaptation, option holders can take either single- or multiple- stage
22 adaptation path. This decision affects a way to incorporate flexibility in a considered adaptation option,

1 subsequently leading to change in economy efficiency. After the coastal adaptation is designed, the economy
2 efficiency of the adaptation depends on how to use the flexibility. The economic efficiency of a single-stage
3 adaptation can be maximised by the optimal investment based on the observation of sea-level rise. On the
4 contrary, the size of an adaptation and the number of stages for upgrade have effects on the economy efficiency
5 of the adaptation - which is represented as option value (NPV_{opt}). Table 1 shows the option values of all the
6 adaptation paths including single-stage and multiple-stage adaptations. The sets of option values for coastal
7 adaptations are the maximum values that decision-makers can gain by the current and future decisions based on
8 the observations and learning. The option evaluation process is explained in supplement 3. In addition, the
9 optimal investment times and option values for each adaptation path are shown by different SLR scenarios and
10 different costs of flexibility.

11

1 **Table 1.** The possible option values for each adaptation pathway according to different sea-level rise scenarios
 2 by flexibility costs

SLR scenarios	Cost flexibility	Adaptation pathways							
		$U_{c \rightarrow 3.0m}$	$U_{c \rightarrow 3.5m}$	$U_{c \rightarrow 3.0m}^*$ $U_{3.0m \rightarrow 3.5m}$	$U_{c \rightarrow 4.0m}$	$U_{c \rightarrow 3.25m}$ $U_{3.25m \rightarrow 4.0m}$	$U_{c \rightarrow 3.5m}^*$ $U_{3.5m \rightarrow 4.0m}$	$U_{c \rightarrow 3.0m}^*$ $U_{3.0m \rightarrow 4.0m}$	$U_{c \rightarrow 3.0m}^*$ $U_{3.0m \rightarrow 3.5m}^*$ $U_{3.5m \rightarrow 4.0m}$
H++	20%	124.8	158.0	156.6	175.4	157.87	160.39	154.08	152.94
	30%			152.9		152.07	157.12	147.76	145.74
	40%			148.6		146.3	151.42	141.46	138.2
	50%			144.5		140.61	146.11	135.2	131
H1	20%	131.4	135.5	151.3	105.8	119.3	135.01	128.03	142.14
	30%			147.4		114.5	129.93	122.46	135.56
	40%			143.5		109.6	124.92	116.73	128.82
	50%			139.7		104.8	120.18	111.33	122.43
High	20%	67.2	36.5	61.52	20.6	35.14	30.4	41.43	42.56
	30%			58.21		31.98	27.8	37.70	38.49
	40%			54.96		29.12	25.5	33.91	34.34
	50%			51.36		26.59	23.5	30.86	30.9
Medium	20%	54.9	25.46	48.5	12.4	24.33	20.1	29.77	29.77
	30%			45.4		21.6	18	26.48	26.48
	40%			42.2		19.31	16.2	23.19	23.19
	50%			38.9		17.29	14.6	20.64	20.64
Low	20%	45.7	17.77	39.3	7.2	16.72	13.3	21.49	21.49
	30%			36.2		14.55	11.5	18.66	18.66
	40%			32.9		12.69	10.1	15.86	15.86
	50%			29.6		11.11	8.9	13.70	13.70
Historic Trend	20%	17.3	1.08	10.9	None	0.92	None	1.89	1.89
	30%			8.3		0.6	None	1.26	1.26
	40%			6.1		0.3	None	0.77	0.77
	50%			4.6		0.06	None	0.47	0.47

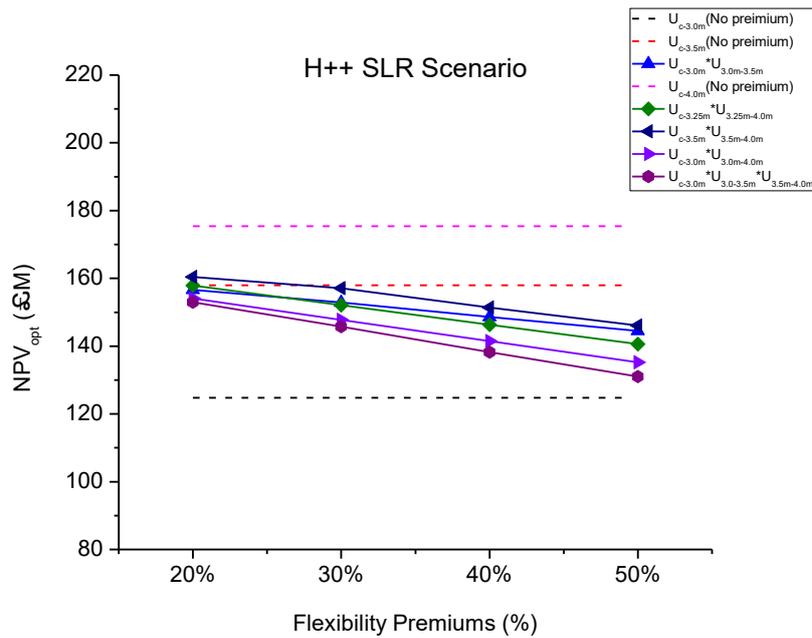
3 * The highest and lowest option values (NPV_{opt}) in each SLR scenario have been written in black and red bold,
 4 respectively.
 5

1 **3.2 Effect of flexibility costs on economy efficiency**

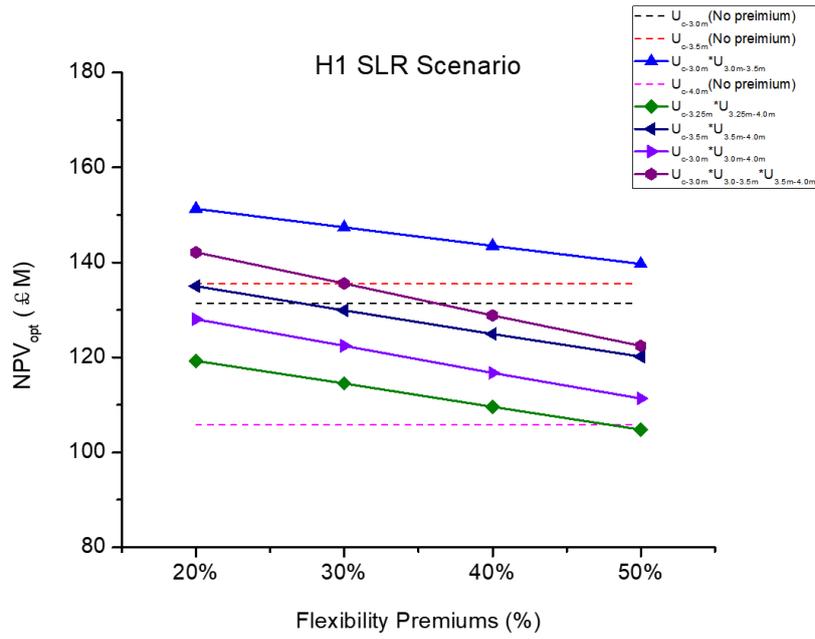
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3 For comparisons between single-stage adaptations and multiple-stage adaptations, the option values of each
 4 adaptation path are plotted across the costs of flexibility under each SLR scenario as shown in Figure 4.

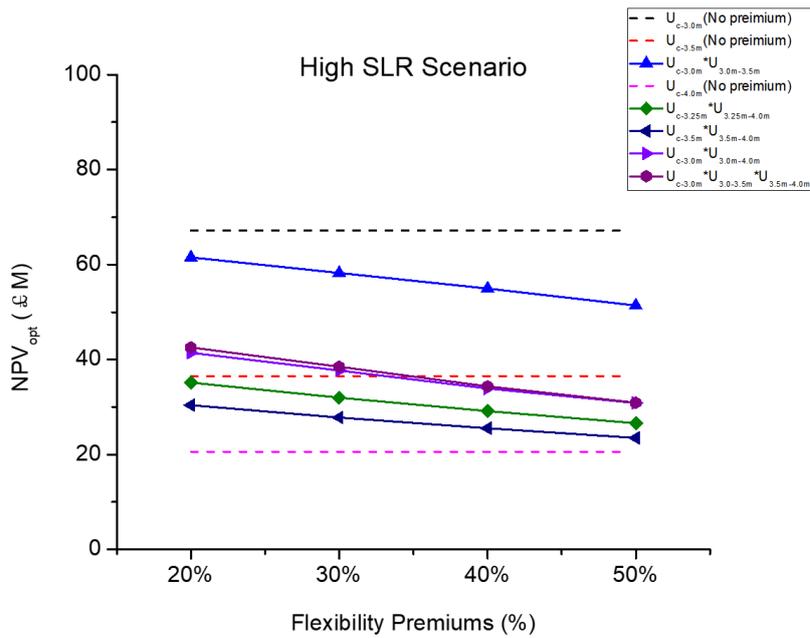
5 For the H++ SLR scenario, the adaptation pathway $U_{c \rightarrow 4.0m}$ shows the highest economic efficiency or option
 6 value among all the adaptation pathways. The single-stage adaptation path of $U_{c \rightarrow 3.5m}$ has the second highest
 7 option value in a range of flexibility cost from 30 to 50%. This implies that the single-stage adaptation paths are
 8 more efficient than the multiple-stage adaptation paths in the most extreme SLR scenario. The risk of the coastal
 9 flooding is very high and sea level is fast-growing at the rate of 2.54cm/year in the H++ SLR scenario so that an
 10 interval between the first adaptation and the next adaptation is relatively short (e.g. 30 to 40 years later). Thus,
 11 splitting investment is inefficient in the worst-case SLR scenario. All the adaptation pathways including $U_{c \rightarrow 3.0m}$
 12 in the first stage are ranked low in the H++ SLR scenario.



13



1



2

3

4 **Figure 4.** Option values (i.e. NPV_{opt}) of optimal investments for each of the adaptation pathways across the
 5 premium cost by different SLR scenarios

6

7 On the contrary, the option values of the adaptation pathways for other mild SLR scenarios (i.e. High, Medium,
 8 Low and Historical Trend SLR scenarios) show different patterns than those for the H++ SLR scenario. The

1 adaptation paths extendable up to 4.0 mAOD show lower performance than the adaptation paths up to
2 3.0mAOD or 3.5mAOD in these SLR scenarios. The adaptation paths including the small size of coastal defence
3 (i.e. $U_{c \rightarrow 3.0m}$) are considered as a more efficient upgrade than those including the large size of coastal defence
4 (i.e. $U_{c \rightarrow 3.5m}$ or $U_{c \rightarrow 4.0m}$). As these scenarios are mild comparing to the H++ SLR scenario in the risk of coastal
5 flooding, the high standard of the coastal defence is not yet needed for Lymington. Thus, the single large
6 investment ($U_{c \rightarrow 4.0m}$) shows much lower efficiency, as shown in Figure 4, than the multiple-stage adaptation
7 paths or the single small investment (i.e. $U_{c \rightarrow 3.0m}$) because the high standard-of-protection coastal defence is
8 considered as an excessive adaptation in such mild SLR scenarios.

9 $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m}$ shows the second highest economy efficiency in managing coastal flood risk under most
10 SLR scenarios except the H++ SLR scenario. If SLR scenarios less severe than the H++ SLR scenario is
11 realised, only $U_{c \rightarrow 3.0m}$ will be made during the 21st century. Thus, further investment will not be made if sea-
12 level rise does not exceed the trigger value (55 cm - which is sea-level rise at 2100 in the High SLR scenario) of
13 $U_{3.0m \rightarrow 3.5m}$ (Refer to Table 3.4 in supplement 3). In this regard, $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m}$ is considered to be an
14 efficient and robust strategy against the uncertain conditions of sea-level rise.

15 For further protection, a set of adaptations that can be raised up to 4.0 mAOD (e.g. $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m} * U_{3.5m \rightarrow 4.0m}$,
16 $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 4.0m}$, $U_{c \rightarrow 3.5m} * U_{3.5m \rightarrow 4.0m}$ and $U_{c \rightarrow 4.0m}$) could be taken as an adaptation strategy.
17 However, these types of adaptations show lower performance than those extendable up to 3.5mAOD level under
18 these mild SLR scenarios. Increase in the overall costs for further protection under mild SLR scenarios leads to
19 the inefficiency or redundancy of the overall adaptation. Nevertheless, these adaptations may be more proper to
20 option holders who prefer to address all the range of sea-level rise.

21 As shown in Figure 4, under the H++ SLR scenario, $U_{c \rightarrow 3.5m}$ is relatively a better strategy in high cost of
22 flexibility (40 to 50%) than the equivalent multiple-stage investment (i.e. $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m}$). It is because
23 the high cost of flexibility increases the overall investment cost of $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m}$. Thus, flexibility does
24 not lead to an increase in economic efficiency under the high cost of flexibility.

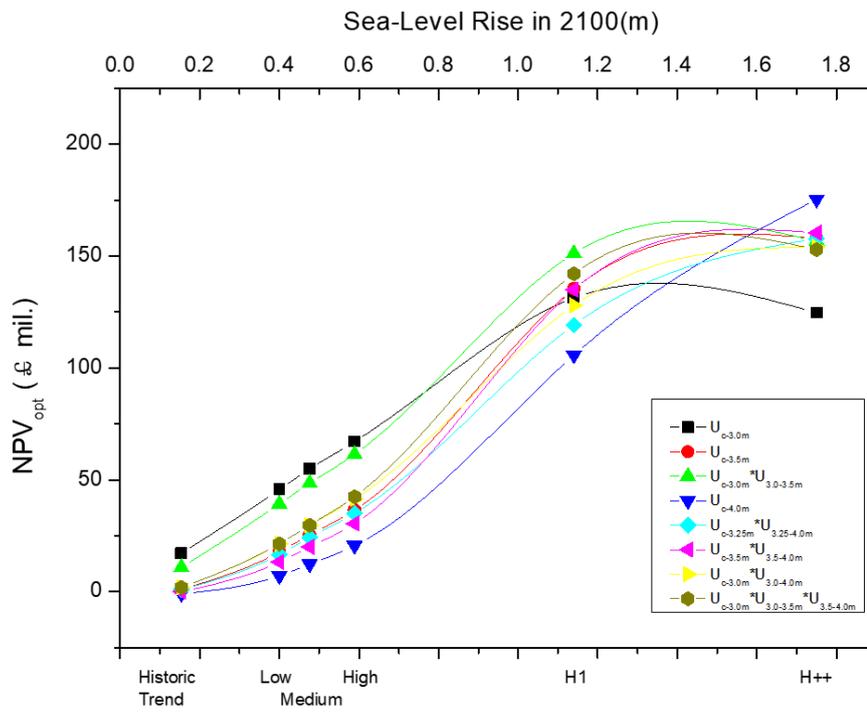
25 As compared in Figure 4, the single large investment in the high standard-of-protection coastal defence may be
26 the best option in the most extreme SLR scenario (i.e. the H++ SLR scenario). However, these types of options
27 show the lowest performance in other mild SLR scenarios (e.g. High SLR scenario). On the contrary, the single
28 small investment ($U_{c \rightarrow 3.0m}$) which shows the highest performance in the High to Low SLR scenarios is the least

1 adaptive to the H++ SLR scenario as it shows the lowest option value in this extreme SLR scenario. Thus, a
 2 robust decision is to take a multiple-stage adaptation path that can perform relatively well across all the possible
 3 future scenarios.

4 3.3 Economy efficiency of different types of adaptations under different SLR scenarios

5 For an illustrative purpose, changes in option value for all the adaptation paths are visualised across the SLR
 6 scenarios in 20% and 50% flexibility premium scenarios (Figure 5). These curves enable us to quantitatively
 7 compare the efficiencies of the coastal adaptations that change according to SLR scenarios as well as to
 8 understand how to trade-off between the most efficient adaptation and the most robust adaptation across all the
 9 range of sea-level rise in 2100. The process of option trade-off is detailed as below.

10



(a) 20% Flexibility Premium Scenario

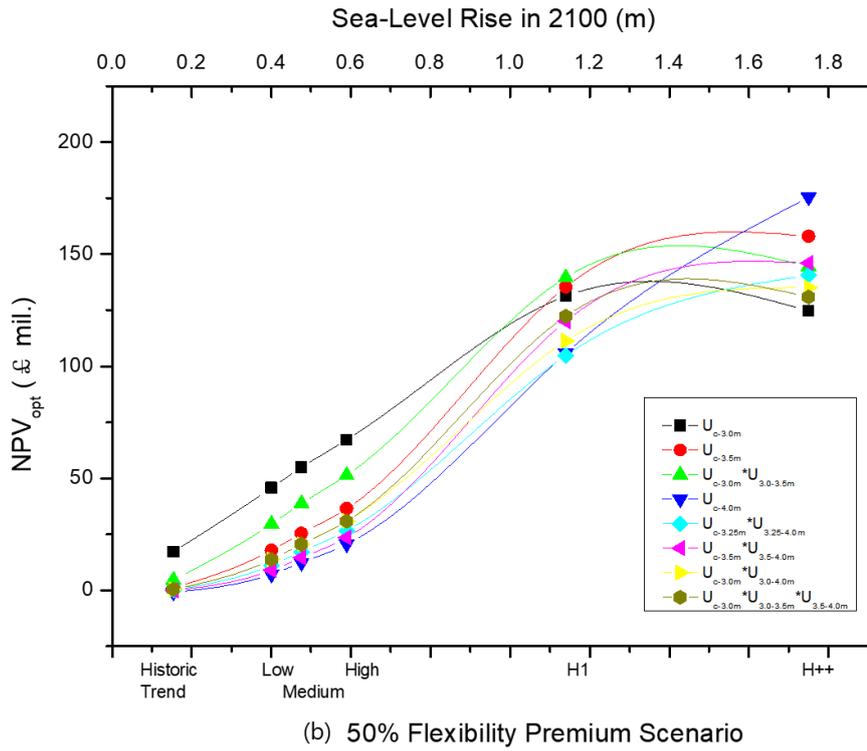
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1

2 **Figure 5.** Changes in the option values of the adaptation paths across SLR scenarios by different flexibility
 3 premiums – Note that the SLR scenarios on the x-axis are equally distanced for the illustrative purpose

4

5 (1) As $U_{c \rightarrow 3.0m}$, $U_{c \rightarrow 3.5m}$ and $U_{c \rightarrow 4.0m}$ are all single-stage adaptations, there is no flexibility cost in these types of
 6 adaptations. When comparing $U_{c \rightarrow 3.5m}$ and $U_{c \rightarrow 4.0m}$, $U_{c \rightarrow 3.5m}$ is more efficient than $U_{c \rightarrow 4.0m}$ in a range from the
 7 Historical SLR scenario to the H1 SLR scenario. On the contrary, in a range between the H1 SLR scenario and
 8 the H++ SLR scenario, the option value of $U_{c \rightarrow 4.0m}$ significantly increases to be higher than that of $U_{c \rightarrow 3.5m}$.
 9 Nevertheless, $U_{c \rightarrow 4.0m}$ is the least efficient if sea-level rise in 2100 is expected to be under 1.6m. Thus, $U_{c \rightarrow 3.5m}$
 10 is more likely to be chosen as an efficient adaptation option when making a choice between $U_{c \rightarrow 3.5m}$ and
 11 $U_{c \rightarrow 4.0m}$.

12 (2) $U_{c \rightarrow 3.5m}$ is a more efficient option than $U_{c \rightarrow 3.5m} * U_{3.5m \rightarrow 4.0m}$. Regardless of flexibility costs, $U_{c \rightarrow 3.5m}$ gives
 13 higher option value across all the SLR scenarios than $U_{c \rightarrow 3.5m} * U_{3.5m \rightarrow 4.0m}$. Thus, $U_{c \rightarrow 3.5m} * U_{3.5m \rightarrow 4.0m}$ should
 14 be rejected in option choice when comparing to $U_{c \rightarrow 3.5m}$.

15 (3) When the flexibility cost is low (e.g. 20%), $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 4.0m}$ and $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m} * U_{3.5m \rightarrow 4.0m}$
 16 may be better strategies than $U_{c \rightarrow 3.5m}$ in the low rates of SLR scenarios. On the contrary, when the flexibility

1 cost is higher than 20%, the economic efficiency of $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 4.0m}$ and $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m} *$
2 $U_{3.5m \rightarrow 4.0m}$ is less than that of $U_{c \rightarrow 3.5m}$ across all the SLR scenarios. The choice of high degree of adaptation
3 paths is an efficient decision when the flexibility cost is low. In the opposite cases where flexibility cost is high,
4 $U_{c \rightarrow 3.0m} * U_{3.5m \rightarrow 4.0m}$ and $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m} * U_{3.5m \rightarrow 4.0m}$ are less useful than $U_{c \rightarrow 3.5m}$ because a low
5 standard-of-protection measure in the first stage makes less efficient such high standard-of-protection
6 adaptations (i.e. coastal adaptations up to 4.0mAOD)

7 (4) In terms of $U_{c \rightarrow 3.5m}$ and $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m}$, we can see that $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m}$ is much more efficient
8 than $U_{c \rightarrow 3.5m}$ in most SLR scenarios. Only in the H++ SLR scenario, $U_{c \rightarrow 3.5m}$ is more efficient than $U_{c \rightarrow 3.0m} *$
9 $U_{3.0m \rightarrow 3.5m}$ because the lifespan of the first stage adaptation is relatively short in the high rate of sea-level rise.
10 However, the option value of $U_{c \rightarrow 3.5m}$ is a little higher than that of $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m}$ only in the H++ SLR
11 scenario. As the H++ SLR scenario is a low-probability case, it is less likely that the option value of $U_{c \rightarrow 3.5m}$ is
12 higher than that of $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m}$. Thus, $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m}$ is likely to be a more efficient adaptation
13 strategy than $U_{c \rightarrow 3.5m}$.

14 (5) As seen in Figures 5 (a) and (d), $U_{c \rightarrow 3.0m}$ gives the highest option value between the Historical SLR scenario
15 and the High SLR scenario. This adaptation provides protection for Lymington at the lowest cost. However, its
16 option value is the lowest in the worst-case SLR scenario. This also implies that the least costly adaptation is
17 very sensitive to the uncertainty of SLR scenarios. In addition, $U_{c \rightarrow 3.0m}$ is a less efficient adaptation than
18 $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m}$ beyond the H1 SLR scenario. This adaptation option is the most vulnerable to the extreme
19 SLR scenario.

20 (6) Lastly, the option evaluation of $U_{c \rightarrow 3.25m} * U_{3.25m \rightarrow 4.0m}$ is included for comparison to coastal adaptations
21 with different increments (i.e. 0.5m, 0.75m and 1m). In relatively mild SLR scenarios (i.e. Historical Trend to
22 High SLR scenarios), single- or multiple- stage adaptations starting with $U_{c \rightarrow 3.0m}$ show higher option values
23 than $U_{c \rightarrow 3.25m} * U_{3.25m \rightarrow 4.0m}$ whereas $U_{c \rightarrow 3.25m} * U_{3.25m \rightarrow 4.0m}$ is estimated to be more efficient than $U_{c \rightarrow 3.5m} *$
24 $U_{3.5m \rightarrow 4.0m}$ and $U_{c \rightarrow 4.0m}$. In the mild SLR scenarios, raising coastal defence up to 3.0 mAOD in the first stage is
25 more efficient than raising it over 3.0 mAOD. However, in the H1 SLR scenario, $U_{c \rightarrow 3.25m} * U_{3.25m \rightarrow 4.0m}$
26 becomes less efficient than $U_{c \rightarrow 3.5m} * U_{3.5m \rightarrow 4.0m}$ - although it seems to be a little more efficient than $U_{c \rightarrow 4.0m}$.
27 As more severe coastal flooding is expected in H1 SLR scenario, higher level coastal defence is more effective
28 in defending the coastal areas. $U_{c \rightarrow 4.0m}$ is still considered to be an excessive adaptation in comparison to

1 $U_{c \rightarrow 3.25m} * U_{3.25m \rightarrow 4.0m}$. In the most extreme SLR scenario, the adaptation starting with 3.0mAOD becomes
2 inefficient options comparing to other adaptations starting with $U_{c \rightarrow 3.25m}$, $U_{c \rightarrow 3.5m}$ and $U_{c \rightarrow 4.0m}$. Thus, in the
3 most extreme SLR scenario, high-level coastal defence upgrade in one stage is better than low-level coastal
4 defence upgrade in many stages, whereas, in the mild SLR scenarios, low-level coastal defence upgrade in many
5 stages is better than high-level coastal defence upgrade in fewer stage.

6 Nevertheless, $U_{c \rightarrow 3.25m} * U_{3.25m \rightarrow 4.0m}$ seems to be much less efficient than $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m}$ across all the
7 SLR scenarios. Thus, $U_{c \rightarrow 3.25m} * U_{3.25m \rightarrow 4.0m}$ is ruled out in the trade-off process. For the given SLR scenarios
8 and coastal defence conditions, $U_{c \rightarrow 3.0m} * U_{3.0m \rightarrow 3.5m}$ is considered as the most efficient adaptation to perform
9 relatively well across all the SLR scenarios.

10 **4. Conclusions**

11 This study demonstrates a real-option based framework to assess a set of adaptation pathways under a variety of
12 SLR scenarios with alternations to flexibility costs. Through the quantification of both single-stage and
13 multiple-stage coastal adaptations including flexibility, we can have important implications in incorporating
14 flexibility into adaptations.

15 Firstly, the real-option based approach enables us to understand how efficient the multiple-stage adaptations are
16 against the single-stage adaptations. As investigated in the result section, the multiple-stage adaptations are not
17 always efficient than the single-stage adaptations. The single-stage adaptations with high crest levels are more
18 likely to be efficient in the extreme or worst cases whereas the multiple-stage adaptations are more robust
19 against the uncertainty of the future. It is because the multiple-stage adaptations provide an opportunity to adjust
20 our plans or investment decisions so as to optimize the coastal flood adaptation to observed future changes. As
21 noted, the size and cost of the first-stage adaptation is crucial for the efficiency of multiple-stage adaptations. As
22 the first-stage adaptation can reduce the current risk of coastal flooding, the benefits from the first-stage
23 investment are monetarily realized in the short term. Thus, the present benefits are more influential on the
24 overall option value than the future benefits.

25 Secondly, the flexibility of wait included in coastal adaptations increases the economic efficiency of coastal
26 adaptations. The flexibility helps decision-makers or analysts learn and observe the future. This flexibility
27 obviously separates the future decisions from the current decisions. The future decisions (e.g. implementing the

1 remaining adaptations) will be made with more information based on the learning and observation. On the other
2 hand, the current decisions concern how to devise adaptation strategies now. The current decisions are of
3 whether to choose single-stage or multiple-stage adaptation or what size of adaptation option is needed. If such
4 decisions are made in the present, the future decisions will be also affected by the current decisions. On the
5 other hand, the uncertainty we are concerned about now will be reduced by the future decision. Thus, the option
6 values of the coastal adaptations will be achieved by the combinations of the current and future decisions.

7 Lastly, there are a myriad of possible SLR scenarios one of which will materialize in the future. It is also
8 possible that none of them will not occur in the future. The likelihood of occurrence of future events is our
9 statistical understanding towards the future from the current perspective. Thus, the future uncertainty always
10 exists in the process of reducing it. As explored in the process of option evaluation, the uncertainty about what
11 SLR scenario we will be on cannot be resolved in real-options based analysis. Instead, we open coastal
12 adaptations to various futures by incorporating flexibility into themselves. In this regard, the option values of
13 coastal adaptations are also uncertain values. For this reason, it is very meaningful that this research estimates
14 the option values of coastal adaptations under each SLR scenario rather than the probabilities of the possible
15 future states are included in option evaluations. Subsequently, if this paper included it, the option value of each
16 adaptation strategy would change depending on decision-makers or analysts' views towards the future states,
17 leading to a different choice of an adaptation strategy.

18 In this paper, other risk drivers such as populations, asset prices and the number of houses or buildings are
19 assumed to be constant over time. Hence, in future applications, the uncertainties about changes in the socio-
20 economy status need to be included for more detailed analysis. This study has upgraded the coastal defence
21 height up to 4.0 m AOD in one or two stages. We could further increase the number of stages, if appropriate.
22 Although it provides more flexibility for adaptation pathways, it does not seem to be an efficient option because
23 the overall investment cost may significantly rise due to premium costs. Thus, the investigation into the degree
24 of flexibility is left for the future research.

25 **5. Acknowledgements**

26 This research is supported by the School of Engineering, University of Southampton (UK). The arguments and
27 opinions revealed in this paper belongs to authors presented in this paper.

1 *The number of words: 7,110 (including figures, tables and references)*

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