ADAPTATION IN THE UK:

a decision-making process

Technical Annexes

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Annex A. Adaptation Decision Making – A Formal Framework

A.1. Decision theory and adaptation: A motivation

Decision theory is a set of intellectual tools that prescribe how we should choose between alternative actions[1]. Decision analyses usually take as inputs information about the risks and opportunities we face, and the options available to us, and generate rules for action that respect our desire for consistency and basic rationality criteria. There is not however a single decision theory. Rather, there are many formalisms that make different assumptions about the structure of our environment, the nature of our information about risks, and how we should evaluate outcomes. Thus a vital part of any decision analysis is an attempt to ensure that the tools we employ are well suited to our decision context. This is often more an art than a science, and can require us to make some difficult ethical judgements, as well as cause us to deeply question where our beliefs come from, and how much we can trust them to be true reflections of the world. The discussion that follows will provide guidance on when it is appropriate to use different methods of decision analysis to decide between adaptation options.

The chief attractions of decision theory are its provision of methods for dealing with uncertainty, its rigorous formal framework which makes assumptions about ethics and the quality of information explicit, and its ability to rank different options quantitatively, thus providing operational tools that are relevant to real-world, resource constrained, decision makers. These three virtues are especially desirable in the context of adaptation decision-making. Climate impacts at the spatial and temporal scales relevant to most adaptations are highly uncertain, and thus an intellectual framework capable of accounting for this is a necessary condition for successful decision-making. Moreover, many anticipatory adaptations – most notably infrastructure investments, regulatory decisions, and sector-level planning - have a public component to them, and are thus dependent on judgements about public attitudes to risk, inequality, and the distribution of policy effects over time. Finally, policy makers and private entities alike often require quantitative analysis in order to justify their actions, whether to the public or to shareholders. Moreover, a careful analytical treatment of adaptation decision problems can help to demonstrate how structural properties of the adaptation options interact with our risk information to determine effective decision rules. These interactions are often quite complex, and the rigorous framework provided by decision theory can provide a method for structuring the problem that highlights important factors and opportunities that less formal approaches may miss. For example, we shall see that measures of the flexibility of an adaptation option, when combined with information about how we expect perceived risks to change in response to new information, can help to determine when it would be best to implement it (see section A.4).

A.2. Decision theory basics – Defining the problem

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[1] Classic expositions of some of the orthodox theory include Savage (1954), Wald (1949), von Neumann & Morgenstern (1944), Luce & Raiffa (1957), and DeGroot (1970). More recent survey treatments are in Resnik (1987), Raiffa (1997), Kreps (1988), and Gilboa (2009). The latter is particularly recommended for modern extensions to the standard theory.

Almost all methods in decision theory have a common structural core. In order to set up any decision problem, one must define a *state space* - the set of states of nature that are possible - and an *outcome space* – the set of outcomes[2]. In theory the state space should be designed to encompass every eventuality that may reasonably be expected to affect the system in question. Moreover, each individual state should be sufficiently precisely defined so that there is no uncertainty about what the consequences of a given action would be were that state to occur[3]. In practice however, a complete enumeration of all possible 'states of the world' that might affect the system is not possible, and we can never be certain of the consequences of our actions. Thus a key part of framing an effective decision analysis is to define a state space that balances the need for a complete description of the world with the desire for computational tractability and ease of interpretation. A good rule of thumb for achieving this balance is to focus on those variables to which your system is most sensitive, and make sure that the state space includes plausible best- and worst-case events. Equal care is required when specifying the elements of the outcome space. These should be given in terms of the decision criteria that are deemed relevant, e.g. economic costs and benefits, likelihood of system failure, non-monetary impacts, or any combination of these. It is thus necessary to decide on relevant decision criteria before beginning the decision analysis. The choice of criteria will also help determine which methods of evaluation are applicable. For example, cost-benefit analysis requires all outcomes to be monetized. If there are important decision criteria that are not readily monetized a different evaluation method may be more appropriate.

Once the state and outcome spaces are defined, the next step is to define the set of feasible adaptation options. An option is feasible if it does not violate any of the constraints the decision maker may face. These may include budget, regulatory, and geographical constraints. It is important, when defining these options, that their characteristics are adequately captured (e.g. Chapter III). For example, their costs, temporal characteristics (e.g. lead-time and life time), risk mitigation abilities, and potential for flexible adjustment, will all be critical determinants of their efficacy.

	State 1	State 2	…	State S
Adaptation option 1	Outcome$_{1,1}$	Outcome$_{1,2}$	…	Outcome$_{1,S}$
Adaptation option 2	Outcome$_{2,1}$	Outcome$_{2,2}$	…	Outcome$_{2,S}$
…	…	…		…
Adaptation option N	Outcome$_{N,1}$	Outcome$_{N,2}$	…	Outcome$_{N,S}$

Table A.1 Defining the problem: states, adaptation options and outcomes

The outcome of this initial procedure, which defines the decision problem, should be a table similar to that in Table A.1. The task of decision analysis is to select a preferred option from the list of feasible adaptation options by coherently integrating this assessment of how different options perform in different states with information about the likelihood of each state. Different decision analysis methods make different assumptions about the veracity and completeness of the information we have about the future likelihood of occurrence of the states, and decision-maker's attitudes to different

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[2] The are some decision models that do not require state-spaces or outcome spaces to be specified. See e.g. Gilboa & Schmeidler (2001).

[3] A further requirement is also needed in conventional applications – that the likelihood of a state's occurrence be independent of any choice the decision maker might make (see e.g. Resnik 1987, p.9). Models that do allow risks to depend on actions are referred to as endogenous risk models, however these can often be reformulated to comply with our generic setup (Shogren & Crocker 1999). There are several famous 'paradoxes' in the history of decision theory, e.g. Newcomb's paradox (Nozick 1969), that can be resolved by ensuring that states are defined so as to be independent of actions. See Gilboa (2009).

outcomes. We now turn to a description of these methods, their assumptions, and their domains of applicability.

A.3. Standard methods of decision analysis

The choice between adaptation options depends on their associated outcomes, and their likelihood of occurrence. To make this concrete, consider the following simplified example:

	No sea level rise	Sea level rises by 1m
Build sea defence	C	C
Do nothing	0	L

Table A.2: A simplified decision problem: The cost-loss scenario.

In this example, the outcomes are measured in economic costs. C is the cost of building the sea defence, which is assumed to perfectly protect against a sea level rise of 1m, and L is the loss sustained if you are unprotected and the sea level rises by 1m. How should one decide whether to build the sea defence? A simple first step is to check whether C is bigger or smaller than L. If C is larger than L, then no matter which sea level rise occurs, the costs of building the defence outweigh the losses sustained if you do nothing. In this case the 'Build sea defence' option is said to be *dominated* by the 'Do nothing' option. It is always rational to remove dominated options from the list of possible options, since one can always do better by choosing another option, no matter which state of the world occurs. If C is less than L, the decision problem is more interesting. In this case which option we should choose depends on what we believe about the likelihood of sea level rise. All else being equal, if we think sea level rise is very likely, we should be more inclined to build the defence. This intuition clearly generalizes – the ranking of adaptation options is vitally dependent on what we believe the future will bring.

A.3.i. Maximizing expected value

Perhaps the simplest method for ranking alterative options is to choose the option that maximizes expected value[4]. When value is measured in economic terms, i.e. in monetary amounts, this method reduces to expected cost-benefit analysis (Boardman et al. 2005). It is possible to consider non-monetized values as well, however we will focus on monetized values since this is the case most widely used in practice.

The expected value of an option is the sum of its probability-weighted outcomes. In order to illustrate this concept, consider the decision problem represented in Table A.2. Suppose that we believe that the probability of sea level rising by 1m is p, and hence that the probability of it not rising is $1-p$. Then the expected values (represented by EV) of the two adaptation options are:

$$\begin{aligned} EV_{\text{defend}} &= (1-p)C + pC &&= C \\ EV_{\text{do nothing}} &= (1-p)0 + pL &&= pL \end{aligned}$$

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[4] An axiomatic derivation of this method was given by De Finetti (1937), although this does some violence to his intentions, as he was primarily interested in deriving subjective probabilities from choice behaviour, rather than justifying the expected value rule.

Thus the expected value of defence is higher[5] than that of doing nothing if:

$$p > \frac{C}{L}$$

This condition tells us when the expected value criterion recommends that we build the sea wall. It makes intuitive sense – the higher the ratio of the costs of the defence to the losses it protects against, the more likely sea-level rise needs to be in order for us to defend.

An important generalization of the expected value method is to allow the state probabilities to depend on time. Until now, we have assumed that the decision problem at hand is static, i.e. does not depend on time. However many adaptation options will be long-lived projects, with time-dependent benefits that accrue over many years. In order to rank such projects it is necessary to be able to compare outcomes at different points in time, and aggregate them into a coherent measure of the performance of an adaptation option over its entire lifetime. Economists have a standard method of achieving this when outcomes are measured in economic value. The method is known as *discounting*, and the recipe is as follows:

i. At each point in time (t), compute the expected value of the adaptation option, $EV(t)$ by using the probabilities of the states at time t.
ii. Multiply $EV(t)$ by the discount factor $(1+r)^{-t}$, where r is the *discount rate*[6].
iii. Add up the results for all time periods to compute the *discounted expected value* (also known as the net present value) of the adaptation option.

The discount rate r is determined differently by different economic entities. Private firms treat r as the 'opportunity cost of capital', i.e. the rate of return that would have been achieved had the money spent on adaptation been invested elsewhere, for example on the financial markets. Public bodies treat r as the social discount rate, which is determined through a combination of ethical judgements[7] and expected growth rates of consumption. The Green Book (HM Treasury 2003) contains guidance on choosing appropriate values for the social discount rate. For projects with long time horizons, it may be appropriate to let the discount rate decline with time. See the Green Book and Groom et al. (2005) for details.

A further extension of the expected value method accounts for how the costs and benefits of a decision option are distributed across different members of society. This procedure, known as equity weighting (Pearce et al. 2006, Boardman et al. 2005), defines the value of an option as the weighted sum of its costs and benefits across different individuals, where the weight on a given individual depends on her income level and a parameter that determines how much we think a change in income affects her 'utility'. We will discuss the concept of utility at length in section 3.2. Here we

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[5] Note that expected value is highest when expected losses are lowest. Since C and L represent losses, we pick the option with the lowest expected losses.

[6] The classic justification of the functional form of the discount factor is in Koopmans (1960). For more up to date discussions of inter-temporal choice see Heal (2005) and Groom et al. (2005).

[7] The ethical parameters required are the pure rate of time preference, and the elasticity of marginal utility (see section 3.2) with respect to consumption (Heal 2005). The appropriate values of these parameters are hotly debated, but the Green book (HM Treasury 2003) provides official guidance. If we are conducting a partial equilibrium analysis in a competitive economy with complete markets (i.e. no externalities, and complete futures markets), and utility does not depend directly on environmental stocks, the social discount rate is equal to the opportunity cost of capital (Heal 2005). These conditions are unlikely to hold in the real world, hence the need to pick explicit values for the ethical parameters.

simply note that expected value analysis can be made to account for distributive effects via equity weights in an *ad hoc* manner, but that these weights are ultimately derived from the more fundamental concept of utility.

Given a value for the discount rate, and possibly equity weights, this extension of the expected value method to the case of many time periods and many individuals can be summarised in the following decision rule:

Choose the adaptation option that maximizes discounted expected value.

For this method to be applicable, several conditions must be met:

1. Outcomes should be measured in economic value.
2. The decision maker should not care about the riskiness of her actions.
3. For public decision makers, the costs and benefits of the adaptation options should be *marginal*, i.e. small relative to consumption levels[8].
4. The decision should be 'once-off', i.e. there should be no possibility of changing the adaptation strategy in the future, or implementing it in gradual incremental steps as events unfold.
5. The adaptation options should be completely reversible[9], the decision maker should not expect to learn anything in the future that may change her beliefs, or it should not be possible to delay implementation until a future date.
6. It must be possible to meaningfully define the probabilities of states, and how they change over time.

It is clear that in many (perhaps most) contexts relevant to adaptation decisions, one or more of these conditions will not be met. In the following sections we present more general decision analysis methods that accommodate such situations.

A.3.ii. Maximizing expected utility

Expected utility theory is the standard method of representing rational choice under uncertainty in much of the economics literature. Conceptually, it involves only a minor adjustment to the expected value method. In practice however this extension may introduce considerable complications into the analysis, to be discussed below. The decision rule is as follows:

Choose the adaptation option that maximizes discounted expected utility.

Despite the innocuous looking difference between this rule and the expected value rule – the replacement of 'value' by 'utility' – this decision method is on much firmer theoretical ground[10], and can also accommodate a broad set of concerns that may be

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[8] By consumption, we mean the set of goods and services (possibly including non-marketed goods such as environmental quality) that people consume. When talking about consumption levels, we will always mean a monetized measure of all these consumption goods, since expected value (and expected utility) methods both usually require outcomes to be measured in a single value measure (i.e. money).

[9] Reversible investments have the property that, if they are made today, they may be sold in the future at a price equal to their initial cost.

[10] The classic axiomatic derivations of the maximum expected utility rule are in von Neumann & Morgenstern (1944), Savage (1954), and Anscombe & Aumann (1963). Savage's result is widely regarded

relevant to reasonable decision makers. The most important of these for our purposes are its ability to represent risk preferences – i.e. how much risk the decision maker is willing to face – and preferences over the distribution of outcomes across different individuals.

In order to specify the expected utility method, we will require the concept of a *utility function*. A utility function is a mathematical function that takes outcomes (i.e. members of the pre-specified outcome space, e.g. a consumption level, measured in monetary terms) as inputs, and maps them into real numbers. These functions represent people's preferences over outcomes, with outcomes that map to high utility levels being preferred to those that map to low utility levels. There are well known methods for eliciting individuals' utility functions from their choice behaviour (Mas-Colell et al. 1995, Gollier 2001). These are of limited relevance for adaptation decision-making, since many adaptation decisions will be public in nature, i.e. will require us to specify societal, and not individual, preferences over outcomes. There are many difficulties with specifying social preferences with utility functions (Boadway & Bruce 1984), and government has not offered explicit guidance on how they should be specified for the evaluation of social projects[11]. Nevertheless, they are widely used in economic theory, and are also important inputs into cost-benefit analysis via so-called 'equity weighting' (Pearce et al. 2006), which we alluded to in section 3.1.

To get an intuition for how utility functions are commonly used in economic theory, suppose that outcomes are measured by a generalized consumption[12] level c, which incorporates all forms of consumption that may be relevant to the decision maker[13]. Then for each value of c there is a corresponding utility level $U(c)$. The function $U(c)$ is generally assumed to be increasing in c, i.e. more consumption leads to higher utility levels, however it need not be linear. For example, the difference $U(20)-U(10)$ need not be the same as $U(100)-U(90)$. In fact, one might reasonably suppose the former difference to be the larger, since a 10 unit change in consumption is likely to affect your utility level more when your consumption is low than when it is high. If we want to impose this intuition on our utility function over consumption in general, it turns out that the utility function must be *concave*[14] in c. Figure A.1 illustrates a typical shape for such a function.

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as the most general, as it derives both subjective probabilities and utilities from first principles, rather than relying on pre-specified probabilities like the other two approaches. It has been called the 'crowning glory' of decision theory (Kreps 1988).

[11] Although the Green Book (HM Treasury 2003) does provide guidance on appropriate values of the social discount rate, which depends on the choice of utility function.

[12] We focus on a single aggregate consumption good since this is a simple, and widely used case. The case where outcomes are given by a multi-dimensional vector of commodities is treated in Kihlstrom & Mirman (1974).

[13] See footnote 9.

[14] For full details on concave utility functions, risk aversion, and much else besides, see Gollier (2001).

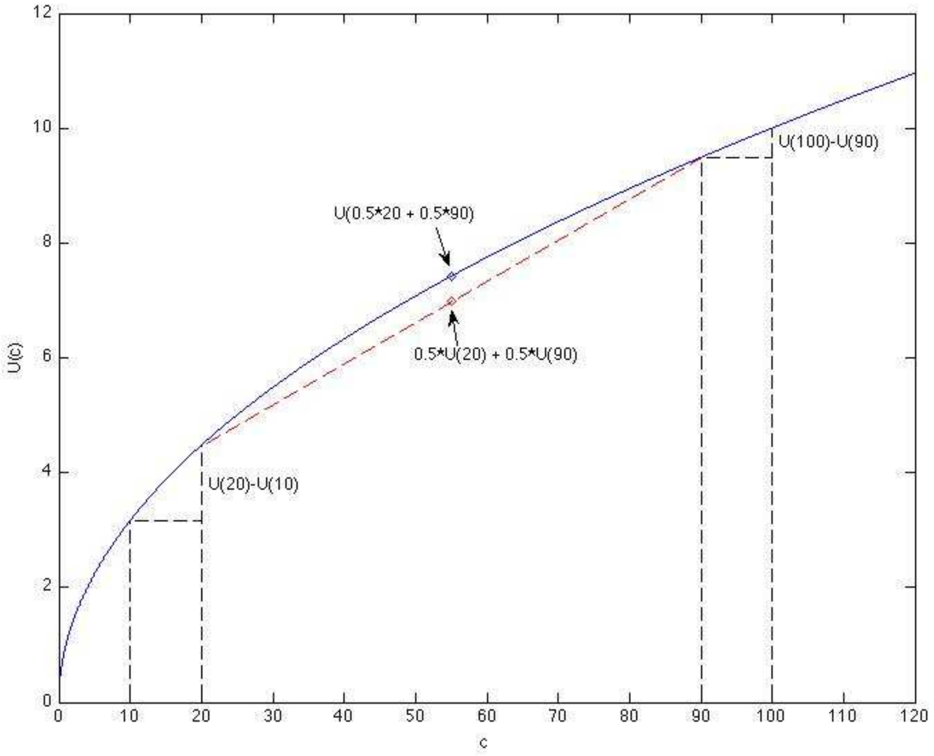

Figure A.1: A concave utility function

The fact that differences in utility decline as consumption increases for concave utility functions gives us a hint as to how it incorporates distributional concerns into the decision process. Suppose that we are considering a costly adaptation option that initially reduces consumption by 10 units. Clearly this will have a larger effect on the utility of those with low consumption levels than on those with high consumption levels. Thus, if we seek to maximize the sum of the utilities of many different individuals[15], those with low consumption levels end up counting more in the evaluation of adaptation options[16]. Similarly, if we are considering adaptation options that are long-lived, and we expect to be wealthier (i.e. have higher consumption) in the future, then our future selves will be given less weight than our poorer present selves, if the utility function is concave. Thus concave utility functions allow us to evaluate adaptation options in a manner that accounts for the distribution of their effects over different individuals, and over the same individuals at different times.

There is however a further important interpretation of concave utility functions - they encode decision-makers' levels of risk aversion. A risk averse decision maker is an

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[15] Such an approach, in which social outcomes are evaluated by summing over the utilities of individuals, is known as choosing a neoclassical (utilitarian) social welfare function. It assumes that the utilities of different individuals are comparable, and cardinal (i.e. differences between utilities are meaningful). For a discussion of the difficult philosophical issues involved in evaluating social welfare, and alternatives to the utilitarian perspective, see Boadway & Bruce (1984).

[16] One might think that individuals with low consumption levels have low utilities, and therefore contribute less to the sum of utilities over individuals. This is true, however adaptation options are evaluated by measuring how much they *change* individuals' utilities. For concave utility functions, the change in utility for a given change in consumption is large for individuals with small consumption, implying that those who are less well off count more in the evaluation of the option.

individual who, given the choice between a lottery with expected value *x*, and *x* for certain, will always choose to have *x* for certain. For example, suppose you are offered a lottery, which pays out 90 consumption units with probability 0.5, and 20 consumption units with probability 0.5. The expected value of this lottery is 0.5*90 + 0.5*20=55. A risk averse decision maker always prefers to get this amount for certain than to play the lottery. To see how this is represented by our concave utility function, consider the expected utility of the lottery. This is just 0.5*U(90) + 0.5*U(20). These two values are plotted as the blue and red diamonds respectively for our example of a concave utility function in Figure A.1. As is clear in the figure, U(0.5*90 + 0.5*20) is greater than 0.5*U(90) + 0.5*U(20). In fact it turns out that for any lottery, the utility of the expected value of the lottery is greater than the expected value of the utility of the lottery, provided that the utility function is concave[17]. The more concave the utility function (roughly speaking, the more 'curved' it is), the more the decision maker is willing to pay to remove the risk from her decision. Thus the concavity of the utility function is a measure of how risk averse the decision maker is[18].

We have seen that maximizing expected utility, rather than expected value, allows us to incorporate attitudes to risk and preferences over the distribution of outcomes into the way we evaluate adaptation options. There is one further restriction that is lifted by using utility functions – we need no longer concern ourselves only with marginal adaptation options, i.e. options whose costs and benefits are small relative to consumption, when evaluating public adaptation options. The expected utility method (or utilitarian welfare analysis) reduces to the expected value method when the costs and benefits of the adaptation option are small – this is the justification of conventional cost-benefit analysis as a project appraisal method for public decisions. However if we use the full expected utility method, we need not make this assumption. For further details, see Dasgupta et al. (1972) and Dietz & Hepburn (2010).

We will make this discussion operational in (cross-reference coastal village case study), where we demonstrate how decisions that account for risk aversion differ from those that simply maximize expected value. For further details on the use of utility functions to represent risk preferences and distributive judgements see Gollier (2001) and Fankhauser et al. (1997).

A.3.iii. Accounting for multiple decision criteria

Up until now we have assumed that decision-makers have a single decision criterion – net economic benefits in the case of expected value methods, or consumption in the case of expected utility. However many decisions, especially in the public sector, may require the weighing up of multiple, incommensurate decision criteria. For example, when considering investing in agricultural intensification, two relevant criteria might be the economic benefits of the investment, and the loss of natural capital (i.e. biodiversity, and ecosystems) that more intensive farming usually entails. There are two approaches to dealing with decision criteria that are not readily expressible in monetary terms: we can attempt to monetize them through non-market valuation methods (Pearce et al. 2006) in which case the decision methods discussed in sections 3.1 and 3.2 apply, or we can treat them as a meaningful decision criteria in their own right, and attempt to elicit people's preferences over them without monetizing.

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[17] In fact this property may be used to define a concave function (Gollier 2001).

[18] In many applications, both theoretical and applied, the same utility function is used to represent attitudes to risk, attitudes to inequality, and attitudes to the timing of consumption. In full generality, all these preferences may be separated, so that different utility functions are used for each of them. See Helgeson et al. (2009) and Traeger (2009).

The decision analysis techniques that follow the latter path are known variously as multi-attribute utility theory (MAUT) (Keeney & Raïffa 1993), or multi-criteria decision analysis (MCDA) (Communities and Local Government 2009). In these methods the effects of the decision options on several decision criteria are determined, and these are then combined into a single measure of the desirability of the option. For example, MCDA usually uses a linear scoring rule[19], with expert determined weights on each of the decision criteria. It has the advantage of explicitly accounting for multiple objectives, however rarely accounts for uncertainty in practice[20]. This would seem to limit its applicability to adaptation decision-making. In contrast MAUT does explicitly account for uncertainty (in manner similar to expected utility analysis), but requires quite sophisticated analysis, both to determine how decision criteria interact in determining decision-maker's preferences, and in specifying the full joint probability distribution over all decision criteria. This makes it difficult to implement without expert assistance, or when information is incomplete. Thus these techniques are probably best applied when respecting the incommensurability of different decision criteria is seen as more important than accounting for uncertainty. We shall briefly return to decision methods that account for multiple criteria when we discuss robust decision theory in section 6.3.

A.4. Irreversibility, learning, and the timing of adaptation

Both the expected value and the expected utility methods make some strong assumptions about the information the decision maker has at her disposal. In particular, they assume that she has well-defined probabilities over the different states of the world, and knows how these probabilities evolve over time. In the following section we will discuss whether the assumption that the decision-maker's information/beliefs should be described by probabilities makes sense in the context of adaptation; this section retains the probabilistic framework, but focuses on how decisions change when we suspect that our beliefs about future probabilities might change as more information is revealed to us over time. In other words, we account for how the prospect of learning something useful tomorrow alters our decisions today.

There are three key factors that need to be present in order for the possibility of learning to affect decision-making. The first is rather obvious – their needs to be some uncertainty over the future, and learning should have a material effect on the extent of that uncertainty[21]. Second, it should be possible to delay implementation of the adaptation options, or implement them in stages. And finally, the adaptation options being considered need to be at least partially irreversible. This means that they should constitute sunk costs which are not fully recoverable, or be subject to adjustment costs if they are to be adapted to new information in the future. Examples of irreversible options include defensive infrastructure projects (no one will want to buy a sea wall that turns out not to be needed), whereas the decision to change the mix of crops planted is well approximated as reversible (you can change back next season at negligible cost).

When both irreversibility and uncertainty are present, learning matters. This is so because decision making no longer involves a simple weighing up of fixed costs and

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[19] i.e., an option is ranked by the weighted sum of its effects on each of the decision criteria.

[20] Although see Stewart (2005).

[21] Learning need not reduce uncertainty, but should affect the probabilities of future states of the world. One models this as future probabilities being conditional on a set of 'signals' that define the set of things one might learn, and how they would affect beliefs.

benefits, since these are contingent on what one might learn in the future. One needs to take account of the value of deciding based on the new information one expects to receive in the future, and weigh this against the loss of benefits from not acting today. In some situations, what one stands to learn in the future is sufficiently interesting to justify more tentative action, or indeed no action at all, today. The economic theory that helps us decide when this is the case is known variously as quasi-option value (Arrow & Fisher 1974, Henry 1974, Epstein 1980), or real options (Dixit & Pindyck 1994), depending on the set of problems to which it has been applied historically[22].

In order to get an intuition for the effect of learning and irreversibility on decision-making, consider the following stylized example. Suppose that you are considering some irreversible and postponable adaptation option – a sea wall will serve as an example – that has a lifetime of 40 years. Suppose that the benefits of the wall are well approximated as certain over a time scale of about 20 years (climate models are in rough agreement about the extent of sea-level rise over this timescale), and that the costs of the wall are known and equal to *I*. However over the second half of its lifetime, the benefits of the wall are uncertain. For simplicity, suppose that there are two possible states of the world from 2030-2050, a low sea-level rise state, and a high sea-level rise state. In the high sea-level rise state, the wall's benefits are high, and outweigh its costs. In the low sea level rise state; assume that the wall's costs outweigh its benefits, so that if you wait until 2030 before building, and discover that the low sea-level rise state will occur, you would not build the wall. Now assume that in 2030 you will learn which state of the world will occur, with certainty. What should you do today? There are two options[23] – build the wall now, or build the wall in 2030 – which should you choose? This decision problem is represented in Figure A.2.

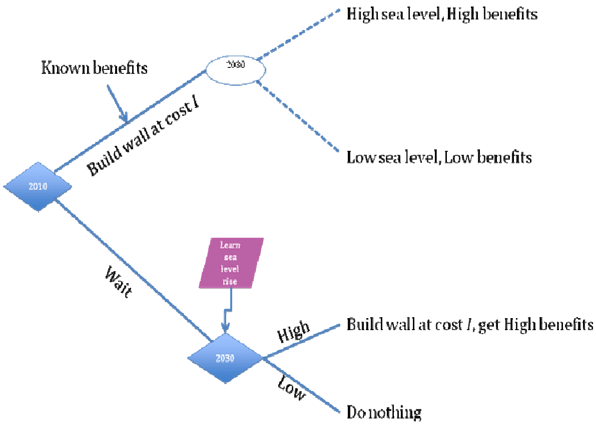

Figure A.2: Schematic of a simple investment timing problem

If we attempted to apply the standard expected value method to this problem, we would simply compute the discounted expected value of the wall, which is composed of its benefits over the first 20 years, and the discounted expected benefits over the next 20

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[22] Historically, quasi-option value emerged out of thinking about problems of environmental preservation (Arrow & Fisher 1974), and often makes use of inter-temporal optimization models with discrete time periods, and conditional probabilities to represent learning (Epstein 1980, Gollier et al. 2000). Real options emerged out of thinking about firms' investment decisions under uncertainty (McDonald & Siegel 1986, Pindyck 1988), and often makes use of continuous time stochastic processes and analogies with the pricing of financial options. The relationship between the two approaches is discussed by Mensink & Requate (2005).

[23] Technically there is also a third option – do not build the wall at all. We assume that the wall's benefits are sufficiently high that this option is dominated by one of the other two.

years. If the discounted expected benefits over the full 40 years are greater than the cost of the wall, this method suggests that we build immediately. However it is possible for the expected value of the 'wait and see' strategy to be greater than the expected value of building the wall today. The expected value of waiting is just the product of the probability of high sea-level rise with the benefits of the wall in this scenario minus its costs, appropriately discounted[24]. This is so since for the 'wait' strategy no benefits or costs are incurred over the first 20 years, and in the next 20 years, we only get some benefits, and incur costs, if the high sea-level state materializes. From the point of view of today, the high sea-level rise state has some probability, so we can compute the expected value of the wait and see option.

From this analysis it should be clear that there are several factors that will increase the attractiveness of the 'wait and see' option, relative to the 'build now' option. First, if there is a large amount to be gained from acting on good information in 2030, i.e. if the potential losses from having built the wall if sea level rise turns out to be low are large, then waiting is attractive. This is known as the 'bad news principle' (Dixit & Pindyck 1994, p.40). Second, if there is large uncertainty in the future benefits of the wall, which will be resolved by future learning, it pays to wait. And finally, if the sure benefits of having the wall between 2010-2030 are small, the opportunity costs of waiting are low, so waiting is desirable. For numerical worked examples that illustrate these results in detail, see Boardman et al. (2005, p.190), HM Treasury (2009), Dixit & Pindyck (1994), and our coastal village case study in Annex B. Irreversibility and learning are discussed in the context of adaptation by Fankhauser et al. (1999) and Reilly & Schimmelpfennig (2000).

A.5. Probabilities in adaptation decision-making

Until now, our discussion has proceeded with the tacit assumption that decision-makers have access to probabilistic information about the likelihood of future states of the world. But is it reasonable (and useful) to describe our beliefs with probabilities when assessing adaptation decisions?

It may be surprising to learn that there are many different theories of the meaning of probability, which philosophers still argue over (Gillies 2000, Hajek 2010). In high school we are taught that probabilities are frequencies. For example, if we take a sample of 1000 newborn babies, and 512 of them are boys, we infer that the probability of being born a boy is about 0.51. The frequentist interpretation of probability is perhaps the most common in the physical sciences, but it is of limited relevance to adaptation decision-making. To see why, consider the following question, of obvious relevance to adaptation: What is the probability of sea-level rise on the coast of East Anglia exceeding 1m in 2080? There is no statistical sample we can take to infer this probability[25]. To be sure, climate modellers can offer us an estimate, for example based on the number of models in their ensemble of climate models that predict sea-level rise to exceed 1m. This would be a frequency-like estimate, but it is not frequentist in the usual sense, since these models constitute educated guesses about the future, and not actual realisations of the past[26]. Moreover, in practice the probability estimates offered by scientists are rarely simple counts of how many models predict a certain event.

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[24] Because you wait in this strategy, all benefits occur in 2030-2050, so need to be discounted.

[25] One would need to run the history of the world forward many times, and calculate the fraction of these histories in which sea-level rise exceeds 1m in order to obtain a frequentist estimate of this probability.

[26] Moreover, how do we know that the ensemble of models is an accurate representation of all the possible future states of the climate? This is the famous reference-class problem (Hajek 2010).

Rather, they are dependent on a variety of subjective judgements about the structure of models, the uncertainty in their parameters, and how to use observations to constrain their predictions (Frame et al. 2005, Solomon et al. 2007, Tebaldi & Knutti 2007).

Could the probabilities that climate scientists provide perhaps then be more accurately described as subjective probabilities? Subjective probabilities measure 'degrees of belief', and have historically been the main objects of interest in decision theory. These probabilities can be derived, at least in principle, from people's choice behaviour. In fact the central results of expected utility theory constitute a set of consistency conditions on people's preferences which ensure that we can describe their choice behaviour as maximizing expected utility over some subjective probabilities of the states of the world. If we believe that these consistency conditions are desirable properties of rational behaviour, we should be able to find probabilities that represent our beliefs. At first sight the consistency conditions required to derive subjective probabilities seem eminently reasonable (see Gilboa 2009), however starting with the seminal work of Ellsberg (1961), a large literature has developed that questions their universal applicability, especially in situations where our information about the world is ambiguous or incomplete[27]. Ellsberg's contribution shows that when we do not know enough about the world we may rationally[28] choose to violate the prescriptions of expected utility theory, thus making it impossible to describe our beliefs with unique subjective probabilities.

It seems fairly clear that the probabilities provided by climate scientists are not subjective probabilities in any traditional sense. Certainly they are in part informed by subjective judgements, but no one would suggest that these probabilities arise from studying climate scientists' choice behaviour. Moreover, many climate scientists are sufficiently aware of the limitations of their knowledge of the climate system (Smith 2002, Palmer & Hagedorn 2006) for Ellsberg's results to be relevant, in which case even if we did elicit their beliefs through choice experiments, we should not expect them to be describable by unique probabilities. This critique is of course not restricted to climate scientists – any decision-maker faced with deciding between adaptation options is likely to be ambiguous about the probabilities of states. She may choose to treat the probabilities provided by scientists as objectively accurate information and maximize expected utility over these probabilities, but that would seem to require some wilful neglect of the extent and nature of uncertainty on her part, or the part of those providing such probabilities.

The probabilities generated by climate scientists are intended to be rigorous objective estimates of the future likelihood of alternative climate states. Yet they are in fact complex hybrids of objective scientific method and subjective beliefs. This makes them difficult to interpret, and assess. The relevant question for adaptation decision-making is whether they are fit for purpose. The answer will depend on the application, and the probabilities in question, however Smith (2007) and Stainforth et al. (2007) suggest that there are good reasons to be cautious of interpreting climate model output as probabilities in general, since models are known to be inadequate at the spatial and temporal scales relevant to adaptation decision-making.

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[27] Binmore (2009) emphasises that even Savage (1954) thought his expected utility theory was only applicable in so-called 'small-worlds', i.e. worlds in which it is possible to imagine and evaluate all situations before they arise.

[28] See Gilboa et al. (2009) and Gilboa et al. (2008).

A.6. Decision-making under deep uncertainty

Despite the cautionary tone of the previous section, it has been forcefully argued that lack of probabilities, and imperfect predictions in general, need not be a limitation on adaptation (Dessai et al. 2009). In this section we explore some of the formal literature on decision making when information about the future is ambiguous or incomplete, and also some more informal approaches, which have recently become popular.

Economists and decision theorists have long distinguished between decisions under risk, in which the relative frequencies of states are known, and decisions under uncertainty, in which there is ambiguity about probabilities, or we are completely ignorant of which state of nature is likely to occur (Knight 1921, Keynes 1921, Ramsey 1931). There is now a large literature that defends various methods of choice in the latter case. Kelsey & Quiggin (1992) offer a useful typology of these methods, classifying them according to whether they make use of non-unique subjective probabilities, unique but non-additive[29] probabilities, or no probabilities at all. We will make use of the same classification scheme.

It is important to be aware when reading this section that many of the decision methods discussed are topics of active research. There is thus still much debate about whether they can (and should) be applied in practice[30]. Our intention is to highlight some of the most important theories of decision-making under deep uncertainty, and comment on their strengths and weaknesses. We do not believe there is a 'best' method, and readers must form their own judgements about the relevance of a given method to their decision problem.

A.6.i. Decision with non-unique probabilities

In this literature authors specify conditions on preferences that imply that decision-makers act as if they have a set of beliefs, each of which corresponds to a different probability measure over the states of the world. Furthermore, they show that these preferences can be represented by mathematical operations that are closely related to taking the expectation of a utility function. Gilboa & Schmeidler (1989) find conditions that imply that decision makers should act so as to maximize the minimum expected utility over their set of probabilistic beliefs. Their recipe is as follows:

Maximin Expected Utility:
Given a set of plausible probability distributions over the states, compute the expected utility of each adaptation option for each probability distribution. Find the lowest expected utility of each adaptation option, and pick the option that has the largest of these.

This formalism encodes *ambiguity aversion*, as decision makers are assumed to always prefer bets with known probabilities over outcomes to those with unknown or ambiguous probabilities. Decision-makers in the Gilboa and Schmeidler framework are very ambiguity averse, as their decision-making is focused on those beliefs that give rise

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[29] Conventional probability measures are additive, i.e. for any non-overlapping (i.e. disjoint) sets of states *A* and *B*, *prob(A* or *B) = prob(A) + prob(B)*.

[30] For examples of current debate, see the recent special issue of Economics and Philosophy (Vol. 25, No. 3, 2009).

to the lowest expected utilities. Nevertheless, their decision rule is simple, and easy to operationalize, making it an attractive option for adaptation decision-making when there are multiple conflicting probability estimates available. The trade-off is that, as with the maximin rule to be discussed in section 6.3, the decision rule neglects potentially useful information that may be present in the full set of probability distributions available to the decision maker. Klibanoff et al. (2005) offer a generalization of this framework known as the *Smooth Ambiguity Model*, which allows for a continuum of attitudes to ambiguity, and incorporates information from the full set of probability distributions. This comes at the cost of needing to define second-order weights on these distributions. It is difficult to see how these weights could be chosen in practice in the context of adaptation, as it is difficult to assess the independence of different climate models (Allen et al. 2006), or meaningfully validate their performance (Oreskes et al. 1994).

A.6.ii. Decision with non-additive probabilities

Schmeidler (1989) provides a very general framework for decision making under ambiguity that describes beliefs with a unique, non-additive probability measure, or *capacity*. The resulting theory suggests that decision-makers should aim to maximize their *Choquet Expected Utility*. Choquet expected utility is analogous to conventional expected utility, except that the mathematical operation of 'taking the expectation', i.e. summing over the probability distribution, is slightly different, due to the non-additivity of the probabilities. This model is closely related to rank-dependent expected utility theory (Quiggin 1982), which has played an important role in behavioural economics. The details of this approach are too technical to be described here (see Gilboa (2009) for an exposition), making this method unlikely to be applied in operational adaptation decision-making. Our intention is simply to make the reader aware of this important work, for the sake of completeness.

A.6.iii. Decision without probabilities

There are several decision methods that dispense with probability altogether. These have the advantage of being robust to the assumptions of a particular model or set of beliefs. They have thus been suggested as appropriate methods for adaptation decision-making (Dessai et al. 2009), since it seems clear that no single climate model can provide objectively relevant likelihood information for most adaptation decisions. While this is a valid point, it is important to be aware that robustness comes at the cost of neglecting potentially useful likelihood information in existing climate models. These methods are cautious by nature – they suggest that since it is not easy to tell when likelihood information might be reliable, it should not be used at all.

There are two decision methods that are widely deployed in this set of approaches: the Maximin rule (Wald 1949), and the Minimax regret rule (Savage 1954). Their prescriptions are as follows:

Maximin:

Compute the worst possible outcome of each adaptation option. Choose the adaptation option that has the best of these.

Minimax regret:

For each state of the world, subtract the outcome of the adaptation option that performs best in a given state from the outcomes of all the adaptation options in that state. The result is called the regret table. Calculate the maximum regret for each adaptation option, and pick the option that has the smallest of these.

The intuition behind the Maximin rule is that in situations of ignorance or ambiguity we should care only about the worst thing that can happen to us. If we pick the adaptation option that has the best of these 'worst things', we are guaranteeing that nothing worse than the worst outcome of this option will occur. Because of its focus on worst outcomes, this rule is very pessimistic. Note that it is more pessimistic than the Maximin expected utility rule, since in this case one is still picking an adaptation option which maximises expected utility with respect to *some* probability distribution. The Maximin rule is not maximizing with respect to anything, it simply assumes the worst. An important advantage of the Maximin rule is its ability to be applied to outcomes which can only be compared ordinally, i.e. we can only say whether one outcome is better than another, but not by how much.

The Minimax regret rule is applicable when what we care about is missed opportunities. The regret table, calculated by subtracting off the best possible outcome in each state of the world from the outcome of each adaptation option in that state, is a measure of these missed opportunities. This rule is less pessimistic than the Maximin rule, and is not subject to some of its more obvious criticisms, such as its indiscriminate neglect of even highly beneficial outcomes. The price to pay for this is that in order to apply this rule outcomes must be cardinal, i.e. we should be able to say how much they differ by in order for the subtraction required to compute the regret table to be meaningful[31].

As a simple example of the application of these two rules, consider our simple cost-loss sea level rise decision problem represented in Table A.2. We assume that the costs of protection, C, are smaller than L, the losses sustained when sea level rises and we are unprotected. In this case, it is easy to see that the worst possible outcome of the 'build defence' option is C, and the worst outcome of the 'do nothing' option is L. Since $C < L$, and recalling that these quantities measure losses, not gains, the Maximin rule will always recommend that we build the defence[32]. Now consider the Minimax regret rule. The regret table is given in Table A.3:

	No sea level rise	Sea level rises by 1m
Build sea defence (regret)	C	0
Do nothing (regret)	0	$L - C$

Table A.3: Regret table for the cost-loss decision

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[31] Technically, one only requires outcomes to be defined up to positive linear transformations. Thus differences in outcomes are defined up to multiplication by a positive constant. See Resnik (1987).

[32] The Maximin rule, when applied to losses rather than gains, becomes the Minimax rule. That is, we find the largest loss associated with each option, and pick the option that has the smallest of these.

In order to calculate the entries in this table, we notice that losses are smallest for the 'Do nothing' option when sea level does not rise, and for the 'build defence' option when it does rise. We then subtracted these minimum losses in each state from the losses sustained by each of the adaptation options in that state to find the regret table. The Minimax regret rule says we should pick the option that has the smallest maximum regret. The maximum regret of the 'build defence' option is C, and the maximum regret of the 'do nothing' option is L-C. That is we choose to build the defence if $C < L\text{-}C$, or in other words, if $L > 2C$. Thus unlike the Maximin rule, which recommends that we build the defence regardless of the magnitude of the losses it protects against, the Minimax regret rule says we should build the defence only if the potential losses are twice as large as the costs of the defence. This is clearly a less pessimistic prescription.

In addition to these two rules, Arrow & Hurwicz (1977) have provided a rigorous derivation of a decision rule under complete ignorance known as the α-MaxMin rule. This rule suggests that decision-makers should aim to maximize a linear combination of best and worst outcomes[33]. Resnik (1987) provides an accessible account of the advantages and limitations of all three of these methods.

Several modifications and specializations of the above rules have been developed in order to facilitate application to a broad class of decision problems. One strategy for specialization is to assume that decision-makers have at their disposal a single best guess model of their environment, and derive decision rules that are robust to model errors of a certain size about this model. Such methods, which attempt to achieve robustness around a best estimate, are said to be *local*. Robustness is usually obtained by implementing a Maximin or Minimax Regret rule over the space of possible models, by assuming that nature picks the 'worst' model at each point in time. This method has been extensively applied by (Hansen & Sargent 2008) in the context of economic theory, but could conceivably be applied more generally.

A related approach, known as Info-gap decision theory (Ben-Haim 2006), provides methods that yield qualitative information about the robustness of decisions to uncertainty around a best guess parameter estimate. 'Robustness' and 'opportuneness' curves are generated, which measure the maximum amount of uncertainty the decision-maker can be exposed to and still ensure that losses do not exceed a given level (in the case of robustness), or the minimum amount of uncertainty the decision-maker must expose herself to in order to have the possibility of achieving a windfall of a certain level (in the case of opportuneness). These curves are then fed into an informal decision process (info-gap does not account for preferences rigorously), in which the decision maker is asked to specify acceptable levels, i.e. the largest loss she is willing to sustain and the smallest windfall she wishes to have the possibility of achieving, and picks options based on their trade-offs between robustness and opportuneness at these levels. A vital part of the info-gap method is the choice of uncertainty model, i.e. how uncertainty is defined and measured. This is an ad-hoc modelling choice, and much of the art in the analysis may lie in picking a model that is suited to the application at hand. It should be emphasized that Info-gap is in one respect less general than the methods employed by (Hansen & Sargent 2008), since it does not achieve robustness to changes in model structure, but only to uncertain parameters or a model.

Aside from their lack of dependence on probabilities, a feature of many robust decision methods is that they do not attempt to maximize anything. Rather they aim to find

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[33] i.e. options are ranked by $\alpha MIN + (1\text{-}\alpha)MAX$, where *MAX* and *MIN* are the best and worst possible outcomes for the option. α can be thought of as a measure of the decision-maker's 'optimism'.

decision strategies that *satisfice*[34], i.e. achieve an acceptable level of some, possibly conflicting, objectives. This is true of Info-gap decision theory, as well as the global robustness methods advocated by Lempert (2002) and Lempert et al. (2004), and applied to adaptation decisions by Dessai & Hulme (2007). These latter methods do not assume a best-guess reference model, but rather use intensive computational techniques to generate a large set of scenarios, and find decision options that satisfice over the entire set. Advantages of these methods include their ability to handle multiple, possibly incommensurate, objectives, and of course their lack of dependence on particular probabilities. The disadvantage is that their ethical assumptions are far less explicit than in traditional expected utility type models and their extensions. In expected utility models decision-makers must explicitly specify, for example, their attitudes to risk (by choosing a utility function) and their preferences for consumption at different points in time (discount rates). These parameters are directly related to their primitive (and measurable) preferences. In robust decision models these ethical parameters are often buried in the choice of acceptable levels for objectives, or the manner in which robustness is measured. It is often difficult to assess what is being sacrificed in order to achieve robustness, and how such sacrifices might relate to decision makers preferences. That trade-offs between robustness and performance are necessary is clear (Lempert & Collins 2007). What is less clear is how they are represented in these decision methods, which often appeal to *ad hoc* intuitive robustness criteria without much justification.

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[34] This neologism was coined by Herbert Simon, and is a portmanteau of 'satisfy' and 'suffice'.

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Annex B. Illustrative Decision Analyses

This Annex presents two simplified decision analyses. The first assumes that probabilities of alterative futures are known, while the second does not.

The analyses are not intended to be directly applicable to real applications; they are highly simplified cases. Instead, they demonstrate the application of different decision analysis methods with the aim of illustrating the types of conclusions they draw and highlighting particular sensitivities.

B.1. Decision-making with known probabilities – the coastal village

This illustrative analysis aims to demonstrate some of the differences between an expected value and a real-options analysis. It particularly aims to highlight the sensitivities of these approaches to the input climate change projections.

The illustration used is a village on the East Coast of the UK, which is susceptible to storm surges and sea level rise. The decision problem considered is relatively simple: how high to build a sea wall, or alternatively, is it better to retreat backwards from the coast ("managed realignment"). The only evaluation criterion used is economic; that is, that the costs of the investment outweigh its expected benefits over the lifetime of the project. Expected utility and value methods, as well as real options analysis, are relevant in this case as there is a single decision criterion and probabilities are assumed known.

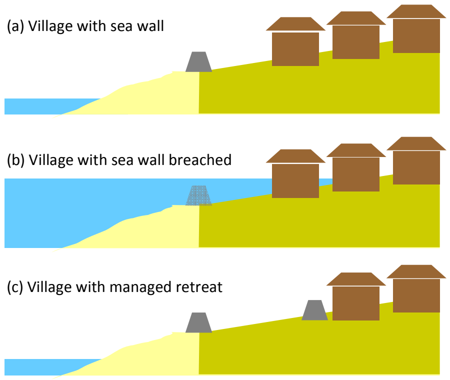
Further details on the coastal village model are given in Box B.1. Importantly, we make the simplifying assumption that climate change only affects the height of storm surges through increases in sea level; we assume that the frequency of storm surges will remain the unchanged. This assumption is not necessarily accurate in reality. We note also that a real case would have more complexities both physically (e.g. complexities in topography, effects of coastal erosion and influence of neighbouring defences) and in terms of the economic analysis (e.g. valuation of ecosystems and agricultural land and multiple decision criteria).

Box B.1 The Coastal Village Model

The coastal village model represents an illustrative, generic assembly of properties close to the coast that is exposed to rare, extreme sea water levels (i.e. storm surges). The village can be protected by a sea wall. We assume the wall has zero risk of failure up to the point where it is overtopped, at which time the wall fails.

If sea level rises such that properties are permanently inundated then we assume that managed realignment is the only option. The model is designed so that this occurs at around 2 metres of sea level rise.

The inputs to the model are simplified but designed to broadly represent levels of risk on the East Coast of the UK. The results are sensitive to the assumptions (particularly regarding topography) and can not be extrapolated to any real town.



B.1.i. Application of decision methods

Our available adaptation options (a sea wall or managed realignment) are both long-lived decisions with high potential sunk-costs. We also know that the village is potentially susceptible to sea level rise and storm surges, given its coastal location and relatively low elevation above sea level. Together, this means that our decision will be highly sensitive to different climate change scenarios. However, we know that there is a high level of uncertainty in sea level rise projections. This arises from structural and parameter uncertainties in current climate models (e.g. in their representation of thermal expansion and melting ice caps), and also missing processes, such as the dynamics of ice sheets (Meehl et al. 2007). The following analyses demonstrate the implications of this uncertainty for adaptation decisions in this coastal village.

Expected value analysis:

Expected value analysis assumes that the decision-maker is equipped with well-defined ('fit-for-purpose') probabilities of different possible future risks. In this case, this means a known probability distribution of sea level rise. In this example, we use distributions based on the UK Climate Projections 2009 (UKCIP, 2009). UKCP09 recognises the ambiguity in sea level rise projections and so does not give full probability-density functions (PDF) (Lowe et al., 2009). However, for the purposes of illustration, here we construct a PDF by fitting a normal distribution to the UKCP09 sea level rise projections for one grid-cell on the east coast of the UK. We use two distributions, one representing the UKCP09 low emissions scenario (B1) and the other, the high emissions scenario (A2). The 5th, 50th and 90th percentiles of these distributions are given Figure B1.1.

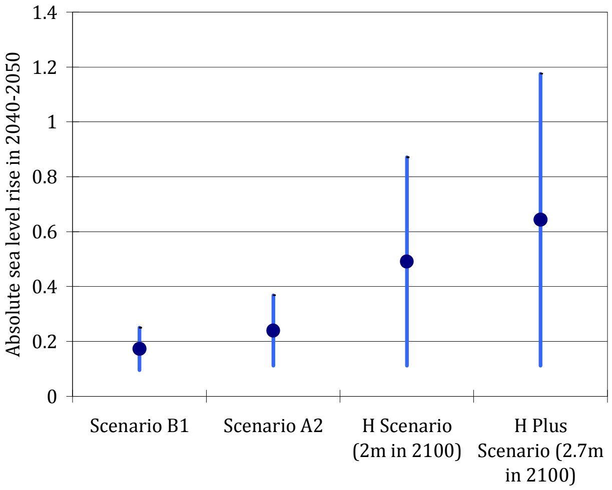


Figure B1.1: The 5th, 50th and 90th percentiles of the four illustrative probability density functions of absolute increases in mean sea level by the period 2040-2050.

For comparison, we also generate two additional distributions representing larger changes in sea level. The 95th percentile of the "H Scenario" is designed to represent the "high plus plus" (H++) scenario given in UKCP09. Lowe et al. (2009) gives this upper bound estimate on UK sea level rise at 1.9m by 2100. They state that this is intended to provide *"users with estimates of SLR and surge increase beyond the likely range but within physical plausibility"* and is useful in situations of *"contingency planning when a higher level of protection might be needed".* It is based on high-level estimates of the possible contributions from processes not currently included in model projections. For sensitivity testing, we also generate an additional "H plus Scenario" that assumes a much higher (2.7m) mean sea level rise in 2100. In both of these scenarios, the 5th percentile is assumed to be equal to the A2 scenario, and the 50th percentile is at the mid-point.

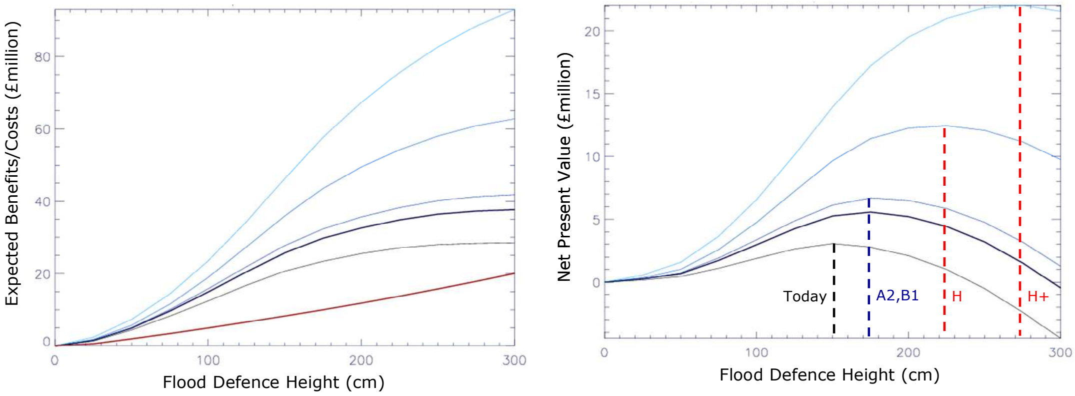


Figure B1.2: (left) Simulated expected benefits (in blue) and costs (in red) for different heights of flood defence; (right) the net present value of the flood defence versus its height. The figures show results for the four sea level rise projections and assuming no sea level rise. They assume an annual discount rate of 2%.

Figure B1.2 compares the costs and benefits of different sea wall heights given the four illustrative sea level rise distributions, based on an expected value approach (Annex A3.i). It also presents a zero sea level rise scenario. The figures suggest that, in this case, with no sea level rise, we should build a wall of around 150cm (based on a 2% per annum discount rate). Based on the two UKCP09-based projections, the optimal wall height is not much changed; it is only around 25cm higher. The reason for this is that the lifetime of the wall is only 70 years. Most 'weight' in the analysis comes from the earlier years (i.e. up to around 2050), and on this timescale the projected increase in sea level is quite small in the UKCP09-based scenarios (e.g. Figure B1.1). This is true even with a low or no discount rate. Also, the specifics of this coastal village mean that while average annual losses increase non-linearly with sea level, high sensitivity is not seen until sea levels increase by around 30cm or more. These results are specific to this particular case. For example, in other cases, such thresholds might be higher or lower (depending on topography and storm surge characteristics) and so the findings are not directly transferable.

Unsurprisingly, greater levels of sensitivity are seen for our two illustrative high sea level rise scenarios. Under the H and H+ scenarios, the optimal wall height is increased to around 225cm and 275cm respectively (or more than 300cm with a zero discount rate). These represent quite significant investments in our model of around £20million for the village (one tenth of the total value exposed). If, for example, we assumed that a managed retreat strategy cost only around £15million (an arbitrary assumption based on estimates presented in Section C.5), then that alternative might be preferable.

Assuming that a decision must be taken today, this raises interesting questions about the extent to which we believe in our two main probabilistic projections (B1 and A2). If we have a high level of confidence in projections, then we might choose to go ahead and build the 175cm wall. However, if we later find that we have under-predicted sea level rise (for example, due to missing processes in the model) and the PDF should have been closer to H (or even H+) then we could incur additional costs in retrofitting or replacing our sea wall, or in scrapping our sea wall in favour of retreat.

Expected value analysis, as applied here, can be useful in identifying such sensitivities. It is not however the best method when ambiguities in climate projections exist – as is arguably the case with sea level rise projections. Expected value analysis does not provide a formal framework to allow a decision-maker to weigh up different options while explicitly accounting for potential ambiguities. Other approaches are available to provide such a formal framework (e.g. see Annex A). One approach that can be useful is real-options analysis. While this also requires probabilities, it allows us to evaluate the benefits of waiting for more information before acting. This is illustrated below.

Real-Options Analysis:

A real-options approach is relevant in situations where we expect predictions to change over time as we learn more. The approach allows a decision-maker to evaluate the benefits of flexible options, including, whether to wait for more information. This type of approach is relevant to the coastal village, as we are evaluating long-lived and irreversible options, and do anticipate improvements in sea level rise projections over time as we learn more about relevant processes (e.g. Lowe et al., 2009). Here, we demonstrate the use of a real options analysis (albeit in a simplified way) to explore the benefits of waiting for more information before acting.

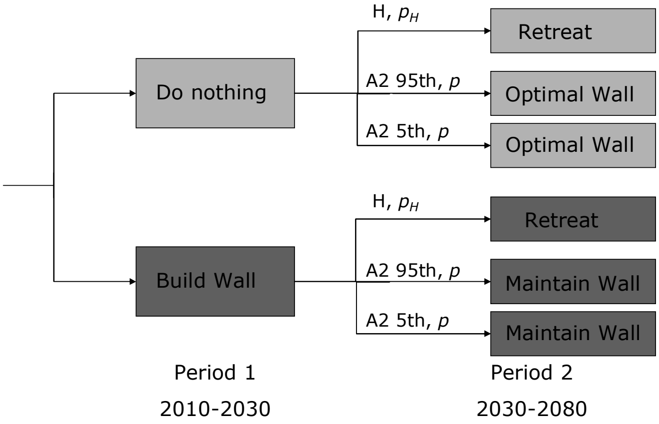


Figure B1.3 Illustrative two-period real options model.

The analysis is structured as illustrated in Figure B1.3. We assume a simple two-period decision-making process. At the start of period one (starting in 2010), we assume we already have a 100cm sea wall. At this stage we are uncertain about sea level rise and have the option to either replace our existing sea wall with a larger one (a 175cm wall) or do nothing. In period two (starting in 2030), we assume that projections of sea level rise are now known with certainly. Assuming we took no action in period one, we can now choose to build an optimal sea wall (if we have followed an A2 scenario) or retreat from the coast (if we follow an 'H' scenario). However, if we already acted in period one, we have no choice but to maintain our existing sea wall or retreat.

We find that the decision of whether to wait or act in period one is highly sensitive to the likelihood we ascribe to the 'H' scenario (i.e. a situation with 2m sea level rise in 2100). This is illustrated in Table B1.1. For example, if the likelihood of 2m in 2100 is only 5%, then it is better to build a wall now. However, if the likelihood were 30%, then it is better to wait for more information.

Probability of the H scenario (p_H)	**Total Expected Value**	
	Period One Action	
	'Do Nothing'	'Build Wall'
5%	£1.1 million	£2.0 million
30%	£1.2 million	£0.6 million

Table B1.1 The total expected value of doing nothing versus taking action in the first period in our simple real options analysis for the coastal village

We find that the threshold is at around 20%. This means that, in this case, if our current estimate of the likelihood of seeing 2m sea level rise in 2100 is 20% or greater, then it would be better to wait for more information before acting. If a decision-maker had a confidence in the current PDF of sea level rise then this probability decision might be simple. However, if confidence was low then an alternative approach might be required, for example, a subjective elicitation of the probability.

Section III.D of the main report describes the application of a real options analysis to a real-world adaptation problem, the management of flood risk in the Thames Estuary and London.

B.1.ii. Conclusions for decision-making

The key conclusions from this analysis for decision making are:

- **An expected value analysis can be highly sensitive to the probability distributions of climate change projections assumed.** It can be useful in testing sensitivities to different input distributions, but other approaches are more helpful in assessing the implications for a decision.
- **Where we expect to learn more over time, and face an irreversible investment decision, a real options approach is helpful in identifying the value of waiting for more information**. Waiting is particularly desirability where the range and chance of high climate scenarios is quite large.
- **Where there are secondary uncertainties in probabilistic projections, it can be useful to have plausible upper and lower bounds to test the sensitivity of decisions to the uncertainties**. Real options analyses can be useful in such circumstances in assessing the conditions under which we would wait for better information before acting.

B.2. Decision-making with unknown probabilities – the water sector

In this example, we explore a case of decision-making where probabilities of different future climates are not known, using a simplified robust decision-making approach. Our case study is a water utility company. This company has the objective to meet water demand in its catchment region until the late 21st century at minimum cost. As such, the decision-maker has two decision criteria:

1. a 'failure rate'[35], defined as the number of times supply does not meet demand over the relevant time horizon (in our case 2006-2079); and
2. the costs of adaptation options that are designed to reduce this rate

There are two broad types of adaptation options: reducing demand or increasing supply.

The decision-maker in this case faces the challenge that we currently have a relatively low confidence in probabilistic projections of the effects of climate change on the relevant precipitation and temperature extremes at the localised scale relevant to water utility companies (e.g. Murphy et al. 2009). Scientists expect projections to improve and change over time as we incorporate more relevant processes and use higher resolution models. In such a situation, current probability estimates could be classed as ambiguous (Annex A). In this case study, we therefore aim to identify adaptation options that are

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[35] In this simplified example we define "failure" as the inability to supply the total demand of water. In practice, failure of a supply system can go from a minor failure, such as hosepipe bans, to a catastrophic failure with long-term and severe rationing of water. Minor failures can usually be managed, while catastrophic failures might be more problematic.

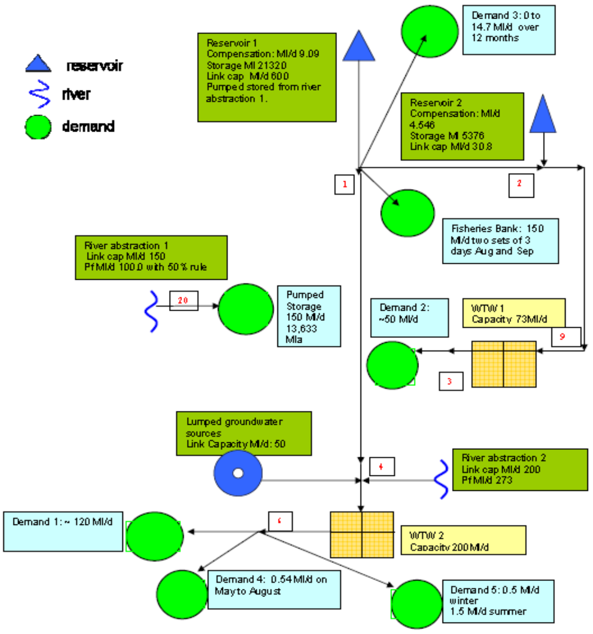
both cost-effective and robust across as much of the range of plausible futures as possible.

The approach explores how plausible changes in precipitation and other climate variables affect river runoff using a water resource model (Box B2.1) and the effects of adaptation options in mitigating these effects. Under historical climate conditions, the model suggests that the system would fail once; during the major drought of September 1976 the system would fail to supply water to ‘demand 1’. Given our defined failure rate criteria, the decision-maker would conclude that the system performs well under current climate conditions. The range of plausible futures is estimated using a large ensemble of different climate model versions of the HadCM3 model (245 climate model runs from the climateprediction.net perturbed physics ensemble[36]; Frame et al. 2009). However, we know from a comparison to other models that the HadCM3 model tends to be relatively dry (i.e. the plausible range may be biased) and that the current range of climate models do not span the full possible range of futures (due, for example, to missing processes); this and other factors, such as limitations of the downscaling approach and impacts model used, must be considered in the interpretation of the results (Lopez et al. 2009).

Box B2.1: The Water Resources Model

Water is supplied by two reservoirs, two river abstraction points and a ground water source (green rectangles). There are seven demand nodes (green circles with blue labels), each of different size and with a defined priority of supply. For example, ‘demand 1’ supplies water within the water resource and is supplied first by the ground water source, then by ‘abstraction 2’ and finally by ‘reservoir 1’. This set of priorities is important when analysing the performance of different adaptation options.

The model is designed to be complex enough to allow for a realistic exploration of different adaptation options, but simple enough to be easily run under a large ensemble of future climate projections



The decision-maker is given four adaptation options:

1. Increasing the storage capacity during high flows by increasing the storage capacity of ‘reservoir 1’ by 18% (denoted, *BIG*).
2. Reducing demand of the largest users (‘demand 1’) by 15%; a targeted demand management initiative aimed at part of the resource zone (*DEM1*).
3. Reducing demand for all major demands (1, 2 and 3) by 15% (*allDEM*). This option could represent a demand management programme across resource zones, since demands 2 and 3 represent water transfers to a neighbouring zone.
4. A combination of the ‘BIG’ and ‘allDEM’ options.

We stress that within this simplified approach we are ignoring important issues such as the environmental impacts of the adaptation options, public response, technical feasibility in a particular water zone and other water usage changes. Moreover, this

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[36] For a description of the experiment see http://climateprediction.net/

simplified case does not include increases in demand over time; in a real case, this could be an important driver of increased risk of failure alongside climate change (Annex C.2). In our analysis, we also neglect the fact that the probability of success of different interventions is not necessarily the same; e.g. demand reduction options might be reversed quickly while supply enlargement options are usually more reliable.

For each of these adaptation options, we calculate the failure rate of the system (the key decision criterion) under the different plausible climate scenarios. The climate scenarios are represented by one metric; the change in 30-year mean summer precipitation between 1960-1989 and 2050-2079. This metric merely represents the overall climate state; this state includes a number of other variables that are important in supply management, such as temperature and winter rainfall. The failure rate is defined as the number of years in the period 2006-2079 in which demand is not satisfied.

Figure B2.1 shows the findings for ‘demand 1’. Unsurprisingly, the risk of failure is highest where precipitation is most strongly reduced, and vice versa. For our case, the bottom panel of Figure B2.1 demonstrates that an increase in reservoir storage is the least effective option in reducing risk at all levels of precipitation change. This is because increasing supply does not help if, in drier years, winter runoff is not enough to make use of the larger storage capacity. In contrast, both of the demand management options are highly effective across the plausible range of futures. The combination of supply and demand measures is most effective when there are large reductions in precipitation, but does not give much advantage over demand measures alone in climates with precipitation reductions smaller than about 40%. In this more extreme case, the different options are closer to each other. This suggests that this system is well designed to cope with variability. In this particular example, this is a result of the fact that one of the possible supply side options, pump storage (Box B2.1), has already been used, and it is so robust that provides benefits in nearly all circumstances.

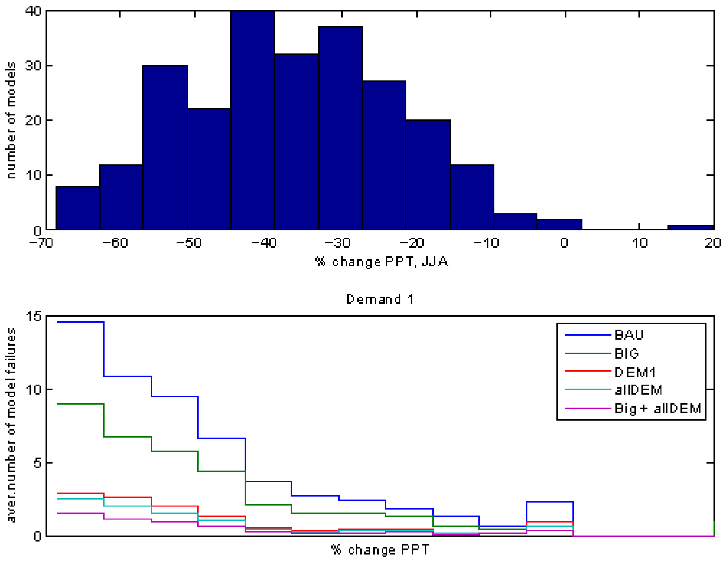

Figure B2.1: Relationship between changes in summer average precipitation, and the failure rates of the five adaptation options at ‘demand 1’. The top panel shows a histogram of the percentage change in summer average precipitation between 2050-2079 and 1960-1989 for the 246 climate projections used in our study. The bottom panel shows the corresponding average number of failures for that precipitation level. This panel gives results assuming no adaptation (denoted BAU, in blue) and the four adaptation options considered.

Similar findings are made for the other demand nodes, though findings are not identical due to the complexities of the system. For example, ‘demand 2’ is less affected by climate change because its water can be supplied by ‘reservoir 2’ if ‘reservoir 1’ is depleted. Also, in this case, measures that aim to reduce all demands are much more advantageous in terms of risk reduction than measures that reduce demand from ‘demand 1’ alone. This emphasises the need to represent all decision-relevant complexities in the model.

The top panel of Figure B2.1 gives a frequency distribution of climate projections based on the one modelling approach used; this can not be interpreted as a probability density function (PDF). If these estimates could be treated as known probabilities then a decision-maker might employ a multi-attribute utility theory to make a decision on an adaptation option (Chapter III). However, given that these frequency distributions can not be treated as probabilities, we might prefer to adopt a robustness approach; that is, evaluating which adaptation options are most effective in reducing the rate of failure under the broadest range of possible futures. This approach to decision making is in the same spirit as the robust decision approach described in Annex A.6.iii.

In order to assess the robustness of the different options across our range of futures, we plot the fraction of climate model versions that meet the criteria - i.e. model versions that have **x** or less yearly failures plotted as a function of **x** for three different time periods. Incorporating a time dimension is useful in generating sequences of adaptation options and considering the option of waiting before taking action. Figure B2.2 shows results for ‘demand 1’; curves close to the top left corner of the graphs correspond to adaptation options with few failures over our range of futures, i.e. they are more robust. As we would expect, as the risk threshold is tightened (i.e. *x* is reduced) the fraction of model versions that meet the criteria decreases.

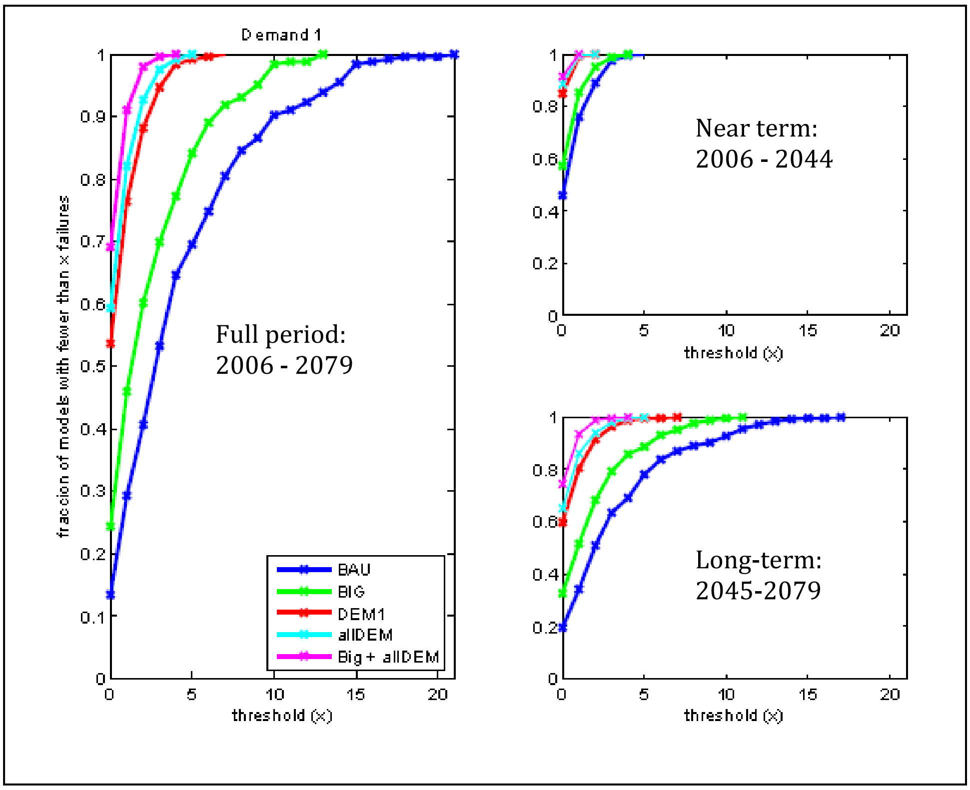

Figure B2.2: Fraction of models for which the number of yearly failures to supply the total volume of water at demand 1 is less than a given threshold. The left panel corresponds to *failures over the full time period (2006-2079), the top right panel to failures between 2006 and 2044, and the bottom right panel to failures between 2045 and 2079.*

Figure B2.2 shows that in the near-term, both the demand management options are effective in reducing risk and there is no advantage from additional storage capacity. In other words, if demand can be reduced by 15%, then the hard infrastructure option can be delayed (if it is needed at all) until we have better information about future climate. In the longer-term (post-2045), incorporating increased storage is advantageous, but in this case, the increase in robustness is not large over and above demand reductions. A decision-maker may choose to re-evaluate this option further down the line (considering the long lead-times of reservoirs, no later than around 2020) when uncertainties might be narrowed. Similar results are found in the other demand nodes.

In addition to the key objective, to reduce the supply failure rate below a threshold, our water company has a second criterion: to use the least cost options to achieve this. Therefore, in order to evaluate options and decide between them, we must also consider their costs.

Adaptation option	AISC (pence/cubic metre) [37]	Yield (Ml/day)	Water saved (Ml/day)	Total cost (over 25 years) £million
BIG	**300-1000**	**15** **25**		**410-1368** **684-2281**
DEM1	**140-160**		**18**	**230-262**
allDEM	**140-160**		**28**	**356-408**
BIG+allDEM	**300-1000 (reservoir)** **140-160 (metering)**	**15** **25**	**28** **28**	**766-1776** **1040-2689**

Table B2.1 Estimated costs of adaptation options

To estimate the cost of each option we use the average incremental social cost[38] (AISC) as a first approximation[39]. Based on these estimates and the strong assumptions underlying them (Table B2.1), the demand management options are significantly less costly than the option which increases supply by extending an existing reservoir.

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[37] AISC estimates from Environment Agency Water Resources Strategy (2009)

[38] The average incremental social cost is the incremental cost of supplying an extra cubic metre of water for the design period (or the life of the asset, depending on how the calculation has been done). In theory it is the best way to compare between options with different characteristics, since it takes into account that some options have high capital costs but low ongoing revenue costs, while other supply methods may be cheaper but need constant renewal or are expensive to run. The main limitation of an AISC comparison is that one has to assume that all schemes are needed immediately in order to calculate the AISC in the first place.

[39] Using this approach we can only compare costs if we assume that the adaptation options are implemented at the same time, i.e. we can not consider the possibility of delaying investment in hard infrastructure for instance, or the fact that introduction of smart metering or changing consumption patterns could easily take about ten years. To estimate the cost of enlarging the *reservoir 1* (for option **BIG**), we consider two different plausible yields after the reservoir enlargement, and assume that the AISC for enlarging a reservoir is similar to the one for building a reservoir. To estimate the costs of reducing demands we assume that the reduction is achieved by introducing universal metering (90% penetration rate). In all cases the total cost is obtained by multiplying the AISC (shown in table 1 for the different options) by the rate of water saved or supplied by the scheme, and by the number of years the scheme will be running (25 years in all cases). We stress that this is a very crude approximation, involving strong assumptions about water saved/supplied by the scheme, and running times, and only provides a rough indication of relative costs.

Despite the simplicity of our analysis, we drawn several useful qualitative conclusions; in particular, we have been able to show unambiguously that, in the near-term, demand-based 'soft' options rank higher than a 'hard' option that increases supply given our decision criteria and the assumptions of the analysis, including the particular characteristics of this water resources system. We have been able to explore how the different adaptation options affect failure rates at different demand sites. These relationships, which are a property of the systems' water allocation priorities and its physical geography, are likely to hold even for adaptation options of different strengths, allowing us to make educated guesses about other options and sites.

B.2.i. Conclusions relevant to adaptation decision-making

This case study demonstrated a simple approach to adaptation decision-making aimed at managing a complex interacting system with multiple decision criteria, and when probabilities are not known. Our model is stylized, but nevertheless captures enough detail of the system in question for meaningful adaptation options to be evaluated. While this case study has explored only one simplified application of robust decision-making, there are a number of conclusions that can be drawn that have relevance to other decision-making examples; in particular:

- **When trustworthy probabilistic information is not available, the insights from robustness-based decision methods can be invaluable.** They provide robust heuristics that can enable successful decision-making, even though nothing is being optimized.
- **Ensuring a system can withstand current climate variability is an important foundation in building robustness to a future climate**. As discussed in Section III and demonstrated here, a decision-maker should assess whether any measures or policies that are beneficial in managing climate variability could increase future vulnerability or limit the ability to adapt. Robustness-based decision-making approaches can be useful tools here.
- In this particular example, we find that **'soft' adaptation measures, such as water demand management, tend to be more robust to climate change uncertainty than 'hard' measures, such as reservoirs.** This result is specific to the case, though studies in other situations have tended to show similar results (e.g. Groves et al. 2008).
- **Robustness-based approaches can help to identify appropriate sequencing of adaptation options, and in particular, evaluate the benefits of waiting for more information before taking more inflexible decisions**. For example, we use such tools here to demonstrate that while 'soft' measures are appropriate in the near-term, after the mid-2040s, supply-based measures may be beneficial under some future climate scenarios. Since the planning period for enlarging a reservoir is about 10-15 years, there is enough time to wait until possibly better climate information is available before making such a decision.

A full robustness-based decision analysis might proceed along similar lines to our example, but would probably consider a larger set of adaptation options, for example, including demand and supply-based strategies of various strengths, and implemented at different times. This would likely make the ranking of options more complex, and may require us to elicit decision-makers preferences for robustness and cost-effectiveness more explicitly, so that trade-offs between these two criteria can be evaluated. However, we have demonstrated that when resources (in terms of computation and modelling expertise) are constrained, an intermediate-complexity approach that draws qualitative conclusions can be useful.

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Annex C. Case Studies

In this annex, we review the characteristics and challenges of adaptation for four case studies: Food, Flooding, Water and Ecosystems.

This analysis aims to demonstrate a high-level application of the decision making framework presented in Chapter III. Following the approach laid out in Figure III.1, we collect information under the following headings:

- **The risk landscape:** assessing current vulnerability to climate and identifying potential future sensitivities
- **Key evaluation criteria for decisions**: this links to the "defining adaptation objectives and constraints" part of Figure III.1 and reviews what determines decision-making today, for example on resource allocation and public policy, and what factors might be relevant in future adaptation planning,
- **Adaptation options:** this section outlines the broad adaptation options available for the sector and their characteristics.

From this information, the main report discuss the key drivers of adaptation decision-making, the range of options, and finally to provide a broad view of the sequencing of relevant adaptation options in light of drivers and uncertainties

C.1. Flooding in the UK

C.1.i. The Risk Landscape

Current exposure of people and properties to flooding: Exposure to flooding is high in the UK; the Environment Agency's 2008 *National Flood Risk Assessment* estimates a total of 5.2 million properties at risk from flooding in England alone; that is, one-in-six properties. Of this, 2.4 million properties are at risk of flooding from rivers and the sea. Just less than a quarter of these are exposed to significant risk, defined as greater than a one in seventy-five (1.3%) chance of flooding. An additional 2.8 million are susceptible to surface water flooding alone (associated with heavy rainfall); this source of flooding is less well mapped, but was the dominant source of flooding in 2007. Additional sources of flooding that are less well quantified include reservoir and groundwater-related flooding.

Many of the exposed properties are protected to some extent, but the residual risks are significant: today, the expected annual damage to property across the UK is estimated at more than £1 billion. Damage from localised flooding occurs relatively frequently in the UK. Less frequently, the UK experiences major flooding that affects large areas and many thousands of people simultaneously. The most recent and severe was the 2007 summer floods when 55,000 properties were flooded and 13 people were killed.

Spatial distribution of risk: The region with the highest total number of properties at risk is greater London (almost 1.1 million properties), but most of these are at low risk and are protected by defences. At higher risk are the Yorkshire and Humber region, the South East, the East Midlands, the North West and South West, which each have more than 200,000 at moderate-to-significant risk. Many rural villages, properties and agricultural lands are at significant risk from flooding and will typically not be protected to as higher standards as urban areas, if at all. The East coast of the UK is most susceptible to coastal flood risk, being exposed to storm surges in the North Sea.

Other risks related to flooding: As well as the immediate risk to life and damage to property, flooding causes a range of longer-lasting impacts, including stress, injury, displaced persons and disruption to economic activity and public services. Important and 'critical' infrastructure, such as energy, water, transport and communications infrastructure, and public services are also vulnerable to flooding. More than half of all water pumping stations and treatments works are in flood risk areas (with implications for water quality as well as service provision), as well as fourteen per cent of electricity infrastructure sites and also significant fractions of emergency facilities, public infrastructure (including schools and hospitals) and transport networks. After the floods in 2007, half a million people were left without mains water or electricity. Infrequent, large floods can also have negative impacts on natural ecosystems. While some flooding is 'natural', a change in flooding characteristics due to climatic changes or human interventions can disturb the equilibrium of the land and ecosystems, which over long-time periods, could lead to morphological change. For example, extensive land drainage and river channelization have resulted in loss of vast areas of wetland in the UK; many habitats and species are now restricted to a small number of sites that are highly vulnerable to alternation in flooding regimes.

Drivers of changing flood risk: In the future, the UK Climate Projections 2009 predicts wetter winters for most of the UK, along with drier summers, particularly in the South East. The severity of changes will increase with rising global mean temperatures over the coming decades. The link between these changes and flood risk is non-trivial and will depend on many local factors. There is also much ambiguity over future localised precipitation changes, particularly for the extreme events normally linked with flooding. Given current understanding, in general, we may expect more flooding due to higher and more extreme precipitation in winter. During summer, we may see a lower frequency of flooding reflecting a drier climate, but more intense flooding when it does occur due to the increased runoff over drier soils. It is not clear when we can expect to see detectable trends in flood risk due to climate change above natural variability; such trends are not detectable today and may remain so for a decade or more to come. Increases in sea level will also mean an increase in coastal flood risk; this effect is much more visible even today. Changes in storm surge frequency would also impact coastal flood risk, but such trends are not yet detected; the most recent estimates from UKCP09 suggest that changes could be small, but they recognise the significant uncertainties in predictions of future storminess for the UK.

A handful of studies have provided quantitative estimates of the effects of climate change on flood risk. These have tended to focus only on river and coastal flooding. For example, in its long-term investment strategy, the EA estimates that under a mid-range climate change scenario (based on UKCP09 and not including new developments), around 60% more properties could be at significant risk of flooding (increasing from 490,000 to 770,000 properties) by 2035. Recent research by the ABI suggests that a global warming of 2°C (expected to occur in the middle or second-half of the 20th century) could lead to an 8% increase in average annual insured losses from river and surface water flooding (from £550 million to £600 million per year) and an 18% increase in 1 in 100 year losses (to around £5 billion). Earlier research by the ABI suggested that with only 40cm increase in mean sea levels, damages from a 200-250 year return-period storm surge (like the 1953 storm surge) would increase from £7.5 billion to £16 billion if defences were not improved.

Changes in land-use and development can also the significantly affect the likelihood and damage from flooding. In particular, urbanisation can reduce natural drainage (increasing run-off and reducing filtration), increasing the risk of surface water flooding. Analysis by Foresight suggests that land-use and urbanisation could have an effect of a similar magnitude to precipitation changes in driving future flood risk, particularly in urban areas. These drivers were assessed as having a lower level of uncertainty than precipitation, particularly in the near-term. Taking account of all these drivers, the Foresight Project in Flood and Coastal Defence estimated that annual flood losses could increase by between £1 billion and around £27 billion by the 2080s, depending on the scenario. In addition, growing populations and development on flood plains also increases the exposure to flooding; this could be a dominant driver of growing flood risk in the short-term. The *Pitt Review* reports that 11% of new homes built since 2000 have been located on flood plains. The ABI estimates that the costs of an extreme flood event (0.1% annual probability) across Thames Gateway could increase by £4 – 5 billion as a result of the new developments, pushing the total costs from an extreme flood in the Gateway to £12 – 16 billion.

In coastal regions, vulnerability to sea level rise can be aggravated by subsidence (for the South and East UK) and coastal erosion (particularly problematic in areas of the East Coast UK). Coastal erosion can itself be accelerated by sea level rise and increased storminess. The increase in risk due to the natural aging and deterioration of current flood protection assets must also be considered.

C.1.ii. Key Evaluation Criteria for Decisions

Current policy context: Flood risk management is implemented by government, individuals and third parties. Typically, government currently plays a central role, particularly in planning and implementing flood protection (resistance to flooding) and ex-post response. Policy is implemented at several levels of government, from national, to regional and local; with the Environment Agency (EA) providing strategic overview. The UK Government has committed to increase public spending on flood and coastal risk management from £600 million in 2007-2008 to £800 million in 2010-2011. Today, England alone has over 25,400 miles of flood defences that help reduce flood risk from rivers and the sea. Two-thirds of the UK's flood risk management budget (around £430 million in 2008-2009) is spent on building, improving and maintaining flood defence measures, including flood barriers and walls, raised embankments, managed river channels and pumps. The Environment Agency (EA) estimates that most new flood defence investments reduce expected damage by at least £8 for every £1 spent, and that between 2003/04 and 2007/08 investments in flood risk management reduced the risk of flooding for around 176,000 properties. The EA's Long-term investment strategy suggests that a steady increase in investment will be required to maintain current defence standards, reaching over £1 billion per year by 2035 (in today's prices) for river and coastal flood risk management alone. Estimates suggest that an additional £150 million per year may be required to mitigate risks from surface water flooding.

Decision evaluation criteria: It is not technically or economically possible to defend all properties from flooding, or to eliminate the risk of flooding completely. In the UK, there is no 'right' to be protected and generally no entitlement to any particular standard of protection. The Agency takes a risk-based approach, considering the probability and consequences of flooding, "to achieve the best results possible using the budget and resources available". Focus is placed on value for money. Rather than a set of national standards for protection, the government provides nationally consistent approaches for appraisal in line with HM Treasury's *Green Book*. Flood management investments are assessed by comparing the costs and benefits of different options, including non-monetary impacts, for example, ecosystems and risks to life. In allocating resources, the goal is to maximum overall benefit to society from investments. Relative benefits of projects are assessed based on a scoring system that takes account of economics (cost-benefit), people protected and environmental protection (with particular emphasis on areas designated for international and national nature conservation). The UK Government has set a target that, in general, flood risk management investments should provide at least £5 return on every £1 spent. The Defra guidance on Appraisal of flood and coastal erosion risk management (2009) also sets out a number of guiding principles beyond cost-effectiveness, in particular related to distributional issues and social justice. For example, national targets are set related to reductions in properties at risk, and specifically deprived households, and protection of ecosystems and sites of special interest. Broader regulations also play a role, for example: EU Directives[40] and UK development control at regional and local authority levels (Planning Policy Statement 25: Development and Flood Risk).

Evidence from current investments suggests that the level of risk aversion is comparable with other developed countries (Nicholls et al. 2007): London is protected from coastal flooding to greater than a 1 in 1000 year standard; many small and large coastal towns are defended to at least a 1 in 100 year and 1 in 200 year standard, respectively; the ABI Statement of Principles suggests that inland and coastal properties be protected to at least a 1 in 75 year standard to be insurable; and the Planning Policy Statement 25 states that no new residential buildings should be build where there is a higher than 1 in 100 year risk of river flooding.

Current treatment of climate change impacts: Flood risk assessments focus on the next 25 years, but recognise changing risks over the coming 100 years. In relation to climate change, Defra guidance calls for a "consistent and risk-neutral approach to considering climate change impacts" and emphasises the use of managed adaptive approaches based on no-regrets actions where possible to maintain flexibility. A precautionary approach, consistent with a level of acceptable risk, is discussed in situations where flexibility is not possible. The 2006 supplementary note on climate change defines time-evolving climate change allowances and sensitivity ranges to be used in project appraisal to ensure consistency and comparability[41].

Who pays versus who benefits? Funding for flood protection and response has historically come from the taxpayer. They estimate the beneficiaries of this investment to include: the public sector (estimated at 31% of benefit); insurers (and indirectly, the domestic and business policyholders, 43%); businesses (11%); householders (10%) and agriculture (5%). Private actors will typically purchase flood insurance (where available); this conveys benefits to the individuals but also to society more generally through risk sharing (also in the UK, there is an element of cross-subsidisation, so more benefit is gained by more exposed insureds). In some cases (particularly for commercial organisations), private actors will reinforce properties with flood resistance and resilience measures and reap benefits from this (usually paying back at the first flood). Uptake of such measures by residential property owners has generally been low.

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[40] Including the Water Framework Directive and Floods Directive

[41] For example, the guidance recommends a net sea level rise *allowance* of +8.5mm/yr for the East of England for the period 2025-2055 (others for other regions and time periods) and for inland appraisals, a peak river flow *sensitivity range* of +20% for large catchments in the 2080s.

C.1.iii. Adaptation Options

There are a broad range of adaptation options for flood risk management, many of which are complementary and beneficial as part of an integrated strategy:

- **Risk information and early warning:** flood risk assessment and mapping to understand who is at risk and inform adaptation strategies; and early warning systems to forecast flooding then warn those at risk as well as responders.
- **Preparedness and response:** well-prepared responsive actions in the occurrence of a flood can significantly reduce fatalities and indirect impacts of flooding; this may include emergency services; evacuation and rescue; temporary protective measures for properties and critical infrastructure; facilities for provision of shelter, food and water. Strategies and support for clean-up and recovery can reduce disruption and distress.
- **Development and land-use planning:** development controls through the planning system to prevent and reduce risks associated with changes in land-use (e.g. deforestation) and new developments and ensure no increases in risk in neighbouring developments.
- **'Hard' infrastructure:** Constructing, upgrading and maintaining flood defences, pumps, flood storage etc.
- **'Soft' infrastructure:** utilising the natural environment to help manage flood risks. These measures can work alongside hard infrastructure or in some cases, replace it. Measures operate through slowing the flow of water, reducing peak river flows and surface run-off. They include: enhanced water retention (by enhancing soil conditions); provision of storage (on-farm reservoirs, enhanced wetlands and washlands); slowing flows (restoring smaller water courses; managing agricultural lands and planting cover crops). Measures can also be applied in urban areas, such as: green roofs to intercept water; permeable paving; surface water attenuation pools; and green flood corridors along rivers.
- **Managed Retreat:** retreating from areas where flood protection is no longer suitable (usually involving moving the line of defences or removing defences).
- **Property-level adaptation:** Property-level flood resistance and resilience measures, such as door guards and dry flood proofing. This can also include purchasing insurance to cover residual property and casualty risks.

Some options will be planned and implemented by government (e.g. early warning systems and most hard infrastructure), some a mixture of public and private actors (e.g. new developments and 'soft' infrastructure) and others only private actors (e.g. property-level adaptation, including insurance). Table C1.1 summarises some of the key characteristics of these adaptation options, including: the economic cost to benefit ratio; the risks; the co-benefits; trade-offs; barriers to implementation; the lifetime (and lead time of decisions); the potential to incorporate flexibility to changing risk conditions; and finally, who pays versus benefits. A fuller assessment is given in Section B.6. The options cover both ex-ante and ex-post measures, with measures that aim to reduce risk (through resistance and resilience; that is, holding back flood waters versus reducing the impacts of flooding when it occurs) and spread residual risk (i.e. insurance). The benefit of an integrated approach that incorporates each of these types of measures is well recognised and was reflected, for example, in the *Pitt Review* and the Government strategy for flood and coastal risk management *Making Space for Water*.

	Economic Benefit to Cost Ratio	Risks	Co-benefits / trade-offs/ barriers	Life-time [Lead-time]	Potential for Flexibility to Changes	Who pays; who benefits
'Hard' Infrastructure	High where high risk levels (e.g. dense populations)	Low risk of failure if well maintained	Can damage environment; reduce perceived risk and increase exposure (new development); can increase downstream risk	Long [Medium to Long]	Low-High *(depending on design)*	Typically taxpayer *(or private);* the exposed
'Soft' Infrastructure	Medium – High *(depending on risk levels, local conditions and specific project)*	Higher risk of failure than 'Hard'	Benefit to environment; alternative land uses rural areas; downstream risk	Long [Medium]	Generally High	Typically taxpayer *(or private);* the exposed
Managed Retreat	High *(depending on displaced land-use)*	Very Low	Potential benefit to environment. Local barriers – displaced uses	Long [Long]	Relatively low *(irreversible decision)*	Typically taxpayer *(or private);* Societal benefit
Development and Land-use Planning	High	Very low	Trade-off with development and other land-uses. Potential co-benefits for environment.	Long [Long]	*Avoids high sunk-costs from new development*	Centrally planned and implemented by private actors; Societal benefit
Property-level Adaptation	Low-High *(depending on risk and if new build/retrofit)*	Medium *(depending on standard)*	Barriers: *lack of responsibility; time and budget; property value; risk perception*	Short-Long [Short]	High	The exposed; the exposed
Risk Information and Early Warming	High	Low *(could reduce failure rate)*	Increased public risk understanding	n/a	High	Taxpayer; Societal benefit
Preparedness and Response Capabilities	Medium	Low *(could reduce failure rate)*	Benefits for all hazards	n/a	High	Taxpayer; Societal benefit
Insurance / risk-transfer	High* _(*but not all risk covered and does not reduce risk, only enhances resilience)_	Low	*Potential disincentive for individual adaptation; financial compensation, not risk reduction or life preservation*	Short [Short]	High	The exposed; the exposed *(directly)* and society *(indirectly)*

Table C1.1: Characteristics of a selection of flood risk management measures.. Note that many of these options can be complementary.

The measures described in Table C1.1 fall into five categories:

- **Long-lived investments involving high sunk-costs:** this includes hard-infrastructure and managed retreat. These investments have potential for lock-in (i.e. it is costly to change them once implemented), but can have high potential economic benefits. In general, these aim to resist flooding (or redirect it in less damaging ways). Hard infrastructure can have negative effects on the natural environment as any changes in water flow, quality and sediment can impact the structure and function of land-based and aquatic ecosystems[42].

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[42] For example, salt marshes and floodplain wetlands require regular flooding and therefore, flood resistance measures can lead to degradation. Similarly, modifications to the morphology of floodplains and channels can negatively impact surrounding and downstream ecosystems. Land reclamation and flood defences in estuaries have greatly reduced inter-tidal areas at the expense of intertidal habitats. With sea level rise, intertidal ecosystems could suffer 'coastal squeeze" as the habitat is prevented from migrating inland by hard boundaries like sea defences.

- **Low-regrets investments with co-benefits:** This includes 'soft' infrastructure. Where implemented well, these types of options can have significant co-benefits for ecosystems, water quality and pollution control, and flood risk management. According to the Foresight study, the economic value of coastal and non-coastal wetlands range from about £40 to £40,000 per hectare per year in 2000 prices.
- **Measures aimed to managing other drivers of increased risks**, such as risk-averse development planning and enhancing natural (e.g. green roofs and paving) and manmade drainage and sewage systems in urban areas.
- **Measures to increase resilience to flooding when it occurs**: including early warning, preparedness and response and insurance. These tend to be reactive and flexible and beneficial under any risk scenario.
- Finally, there is **property-level resistance and resilience building**, which can include temporary and permanent, anticipatory and reactive measures.

A comprehensive decision-making process will evaluate each of these options and their role in short and long-term flood risk management. This process should evaluate options against each of the relevant criteria, for example, cost-benefit, protection of people and properties, environment protection and distributional issues[43].

Some types of options have been traditionally under-used due to various barriers to implementation (*see Pitt Review*). For example, implementation of property-level resistance and resilience building is rare, particularly for residential properties, despite being highly cost-effective in flood exposed regions. Barriers include: low risk perception; concerns over a potential negative impact on property-prices; budgetary constraints; visual appearance; and concept that flood management is the responsibility of government or the insurer. The assessment of policy options to overcome such barriers and conflicts where appropriate to achieve broader societal goals is an important component of government decision-making. Another group of options with historically low take-up rates but potentially high benefits is the soft adaptation options; due, for example, to a lack of information and experience (these approaches tend to be considered more complicated than conventional hard infrastructure approaches, with less certain benefits), and in some cases, the need to modify private lands.

C.2. The UK Water Sector

C.2.i. The Risk Landscape

Current exposure: Levels of water availability in the UK are defined by a combination of rainfall, population density and industrial concentrations. The areas of the UK at highest water stress are the South and South East; these regions have comparatively less water per person than some hotter and drier countries in Europe like Italy and Spain. In 2008, per capita domestic consumption (ppc) ranged from 107 litres per person per day to 176 litres per person per day, with the highest use per person concentrated in the South East. Industry is the other major user. The agricultural demand for water (mainly irrigation) is regionally and seasonally varied, but mostly concentrated in East Anglia and parts of the Midlands. Irrigation accounts for around 1% of total abstraction but is concentrated at the time of the year when flows are at their lowest, and little water is returned to the environment. On a hot dry day there can be more water abstracted for

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[43] There are a number of distributional issues involved that go beyond the scope of this study. These include for example, less wealthy people tend to live in higher risk regions with lower affordability of insurance and property-level adaptation. In addition, rural areas and agricultural lands receive less government-funded protection typically as a result of the lower economic benefits of these investments.

irrigation than for public water supply in some catchments (DEFRA 2008). Energy production requires large amounts of water for cooling, and lack of water has caused power cuts when nuclear power stations have to be shut down during droughts. Leakage from pipes is also a demand for water. A certain amount of leakage is unavoidable and is allowed for when planning how much water is needed.

Water is abstracted from rivers, groundwater and supply reservoirs. The contribution of each varies by region. For example, in the South-east, seventy-percent of supplies come from groundwater (Arnell and Charlton 2009), whereas the North West region is largely dependent on surface-water. This means that across the UK there are differing susceptibilities of water supplies to climate[44]. Rainfall levels vary significantly by region, and also over time (seasonally and annual). Current water management systems are designed to cope with this. This means that, in general, the likelihood of a complete failure of supplies is very low. For example, during the autumn/winter drought of 2003 (that accompanied the summer heatwave), no hosepipe bans or restrictions on essential water were required (though spray irrigation restrictions were widely used) as a result of mitigation measures and good antecedent supply conditions. However, the system can be susceptible to extended drought periods, for example: the 1975-1976 drought caused major problems for both surface- and groundwater-fed catchments with routine rota cuts of up to 17 hours a day in the South East of Wales, standpipes and water rationing in Devon, Cornwell and South East of Wales; and during the long drought that lasted between the spring of 1995 and the summer of 1997, water supplies were restricted through statutory measures that included drought orders, garden watering bans and hosepipe bans in different areas (Cole and Marsh (2006), and references therein). It is possible that some water management systems would be unable to cope with severe droughts of the scale experienced in the more distant past; for example, during the droughts of the early nineteenth century[45].

Water supply and treatment infrastructure in the UK is highly exposed to flooding, as was demonstrated during the 2007 summer floods (see section B.2.i).

Other risks related to water use: Water quality is an important issue, both for natural and human systems. For example, the way in which water is used and released back to the rivers impacts on rivers ecosystems. Polluted drainage from urban and agricultural areas into surface water can lead to water quality issues, creating an imbalance in riverine ecosystems. For example, agricultural activities contribute 60% of nitrates and 25% of phosphorous water pollution, principally trough manure and fertilisers. Such diffuse pollution is a significant problem for groundwater sources; nearly half of the groundwater used for public water supplies is affected and has to be either blended clean water, treated chemically or replaced by other sources.

Water management systems have other negative impacts on the local environment. For example, in some regions (particularly in the South East of England) current levels of abstraction are causing unacceptable damage to the environment at low flows.

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[44] For example, the North West region is most susceptible to short duration droughts (one to two seasons), particularly those that occur during the spring and the summer when demand is highest. Whereas, the Anglian region is vulnerable to long duration droughts when flows have been low for over 15 months and winter groundwater recharge has been minimal. In groundwater-fed catchments exceptionally hot summers (i.e., 2003) can be accommodated if there has been adequate winter recharge.

[45] For example, the East of England experienced severe droughts in the nineteenth century that would present a significant problem for current water resource systems. An analysis of early nineteenth century droughts showed that yields would have been up to 16% less than the estimates based on 1920-2004. The same study projected that changes in long-term climate will affect reservoir yields by ± two per cent by the 2020s (Wade, Jones and Osborn, 2006).

Non-climate-related drivers of changing risks: Today and in the near future, the dominant driver of increased stress on water resources is related to increased demand for water, caused by changing population densities and consumption. In some cases, this will need adaptation in the next decade, with or without climate change. The uncertainty in the scale increases over time and is on-par with climate-related uncertainties.

- The population of the UK is expected to rise; assuming a population growth of 5 million in England and Wales by 2020, the household demand for water would increase by 6%, or about 500 million litres per day (500Ml/d).
- Concurrently, per capita household water consumption could decrease as a result of metering, tariffs, and water saving initiatives. DEFRA (2008) estimates that the average per capita consumption could fall to 120 litres a day by 2030, with appropriate incentives and regulation.
- Growth in industrial and commercial consumption will depend on a combination of sector growth and potential improvements in water efficiency. For example, the food industry has committed to reduce water consumption by 20% by 2020. If all sectors adopted this, demand would reduce by 2000Ml/d.
- Leakage levels will depend on the strength and direction of regulation and the technology available. Water companies project a reduction by 2% between 2015 and 2035. The Environment Agency estimates that, with current technology, a reduction of leakage of about 30% (1000Ml/d) by 2025 can be achieved.
- Changes in land use can affect the amount of water that makes its way to the water environment. For instance some forms of afforestation or a move to deep-rooted biomass crops could negatively affect water resources, while less water intensive crops can have a positive effect.

Combining all these drivers, water demand across the UK is expected to rise steadily over the next 10 years, reaching 5% more than what it is today, mainly as a result of population growth and demands from industry. By the 2050s, across the four demand scenarios developed by the Environment Agency, the projected changes vary between 15% less than today and 35% more.

We also note that water supplies are impacted by changing environmental obligations to protect the river ecosystems.

Climate-related drivers of changing risks: Over the coming decades, we expect climate change to play an increasingly prominent role. Projected higher temperatures, wetter winters and drier summers, as well as changes in the distribution of rainfall, will impact available water levels. The Environment Agency estimates that by 2050 average river flows across England and Wales might increase by 10 to 15% in winter, and reduce by over 50% (and up to 80% in some catchments) in late summer and early autumn. The total annual average river flow could drop by up to 15%. By 2025, the overall recharge to aquifers is expected to decrease, river flows fed by groundwater decrease, and there will be a general lowering of groundwater levels. Changes in the temperature of water will affect river ecosystems. Water supply systems are also susceptible to changes in extreme events. Extreme droughts (like 1975/76) and floods could become more frequent. We may also see more extreme drier winters, lowering recharge of reservoirs and aquifers.

In addition, it is estimated that climate change will cause an increase in domestic demand by between 2 and 4% by 2050. Demand for water for irrigation could increase by 25% by 2020. The potential impact of climate change on increase demand in this sector could be high, and could move northwards and westwards in the UK. By 2020s central England and the eastern margins of Wales could experience conditions similar to the south and east of England today. Changes in peak demand during the hot summer months will affect the reliability of the distribution system.

Problems of water quality could also be worsened by climate change. Extreme summer rainfalls, such as those experienced in England and Wales in 2007 and 2008, could cause significant amounts of dry, loose soil and associated debris to be washed off hill sides into rivers, lakes and reservoirs, causing diffuse pollution. Lower flows during the summer may also lead to greater concentration of pollutants, increasing the cost of water treatment. Higher peak flows may increase sediment concentrations or flushes of pollutants, threatening abstractions.

The net effect of these changes depends on management. A reduction in summer low flows is very important if water is abstracted directly from the river, but less important if taken from a reservoir recharged during the winter. Effects of changes in river flows on reservoir reliability depend on the reservoir storage and design yield. However, it is possible that as a consequence of changes in climate risks, the infrastructure designed to cope with past and present climate variability may become inadequate. Some critical infrastructure such as reservoirs, groundwater sources and river intakes could become less reliable if current operational rules are maintained,. The importance of climate change as a driver of water resource management varies depending on the water resource zone. From current water management plans, in many cases, climate change (as opposed to demand) does not drive any resource development or investment decision over the regulated 25-yr planning period of a water company.

C.2.ii. Key Evaluation Criteria for Decisions

Public water supply and sewerage in England and Wales is provided by private sector companies under long term license agreements, subject to environmental and economic regulations. There are currently twenty three water companies in England and Wales that supply domestic, industrial and agricultural consumers, excluding irrigation. The government plays a key role through setting the regulatory framework to ensure: (i) that customers benefit from fair and affordable bills; (ii) that a clean, safe and reliable water supply is maintained; and (iii) that the environment is protected (DEFRA 2008).

Regulatory standards: Security of water supply is tightly regulated. Water companies must secure supply complying with certain "reference level of services" which state the frequency with which companies can impose different types of water use restrictions during periods of water shortage[46]. Cost-effectiveness of achieving this standard and value for the consumer is also regulated. The Office of Water Services (OFWAT) is the economic regulator that determines investment levels by fixing limits on price increases. There are additional regulations related to: the quality of water delivered (The Water Drinking Inspectorate); methodologies for the calculation of water resource availability; and the environmental impact of abstractions and discharges. The broad regulatory context for water supplies is set by DEFRA for England, the Welsh Assembly for Wales, and by directives from the European Union.

Planning: The water supply companies in England and Wales are legally required to prepare periodic water resource management plans (WRMP). These plans focus on investment decisions over the following five years, but taking into account how they plan to secure water supplies over the next 25 years while at the same time protecting the environment and meeting required water quality standards. The WRMP consists in

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[46] At present, the reference level of service broadly specifies that demand may be restricted by up to 5% for between 3 and 12 months once in 10 years, and by an additional 5% with drought orders once in 40 years.

evaluating the amount of water available for supply as well as all the demands for each year until the planning horizon. This is done under the “dry year” annual average scenario (a period of low rainfall and unconstrained demand) as the norm, but a “normal year” and a dry year “critical period” are also explored to test sensitivities.

For all new options proposed for inclusion in the WRMP, water companies need to consider the impact of climate change on the deployable output and the contribution that they would make to climate change adaptation in the company. Water companies use industry-agreed procedures for estimating future deployable output of their supply systems (Environment Agency 2008b, UKWIR 2007). The process of evaluating possible options and choosing the one that will allow the water company to comply with its statutory obligations follows the guidelines set out by the Environment Agency (2008). If a supply-demand deficit is identified during the planning period, the company has to plan the actions to be taken to resolve the deficit. In the last periodic review in 2009, in the majority of WRMP, the planning options adopted focused on build overall resilience to the range of interacting future pressures. Climate change specific options were not explicitly introduced (Charlton, Arnell 2009). The companies’ adaptation strategies are usually determined by the need to satisfy regulatory requirements by providing current levels of services and enhancing them where necessary, and the desire to maintain their reputation (Arnell, Dellaney 2006).

Who pays versus who benefits? Today, the required investments in water management are funded by the water bills. Price regulation allows the companies to raise enough revenue through the bills to provide the service, to pay directly for a proportion of the investment they are required to carry out, to pay interest on long term loans raised to finance the investment and to cover dividends to investors. In this way current customers can see the benefits as soon as the projects are completed, and future customers share the costs since they will be benefiting from long lasting improvements[47].

C.2.iii. Adaptation Options

Given current regulation, the goal of any adaptation option will be to guarantee the meeting of the standard levels of service in a way that is cost-effective and compatible with the environmental regulations. Adaptation options can be categories as follows:

- **Resource-based:** options which increase the available water output through the gaining of additional water supply (such as new boreholes abstractions, creating or enlarging existing storage (reservoirs and winter storage), desalination plants, new groundwater sources or increased river abstraction).
- **User-based demand-management:** measures which optimise water use efficiency through education, advice, tariffs, metering, water-efficient equipment and fittings, water-reuse and recycling, and other means.
- **Distribution management:** measures which improve the efficiency and flexibility of the distribution network, such as leakage management and increased connectivity of resource zones (bulk transfers), wastewater re-use.
- **Production management**: measures used at the production stage to improve capacity and efficiency such as blending, treatment, pumping regimes etc.

These options have very different characteristics:

- There is a group of options that are **faster to implement, flexible and have benefits under any scenario**; this predominantly includes the user-based

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[47] Water UK, Finance and investment briefing notes
http://www.water.org.uk/home/policy/positions/finance-and-investment

demand management initiatives. These could be considered 'no-regrets' strategies.

- Reduction of demand through leakage reduction could also be 'no-regrets', but there is a point where reducing leakage is not cost effective anymore.
- At the other end of the spectrum, are the long-lived hard-infrastructure investments, associated for example, with new sources of supply. These **options have long lead-times and lifetimes, and generally a lower level of flexibility to changing conditions**. For instance, including the time required for planning application and public consultation and the building of the reservoir, it can take between 15 and 20 years to have a new one in place, and between 5 and 10 years to enlarge an existing one. These options also have more constraints on application[48].
- Other options, such as transfer of water to share resources between different zones, might be low- or no-regrets, these can be implemented in a few years, and make a better use of existing infrastructure if there is a surplus of water in a resource zone close to one with a water deficiency.

The EA estimates that the **average incremental social costs AISC**[49] of some of the management options as: near universal (90%) metering 140-160, groundwater development 100-500, surface water development 100-500, new reservoir 300-1000, desalination plant 400-800 (units: pence per cubic metre). In water resources planning an option with a lower AISC is preferable to one with a larger AISC.

Given the importance of security of supply, **reliability is a crucial decision criterion**. In the context of managing climate, some options will be more reliable than others. For example, the Environment Agency Water resource strategy 2009 suggests that effluent re-use and desalination will be more reliable than rainwater harvesting, direct river abstractions and reservoirs. The options that will provide increased resilience include greater local and inter-basin connection between supply infrastructure, improved base flows in rivers through land management techniques, more re-use of highly treated effluent, using water storage, desalination, conjunctive use of supplies from different sources, conjunctive use of resources with demand management.

The suitability of different options under climate change depends on the water resource zone. According to the last WRMPs in some regions, climate change in the next 25 years will have mild impacts, and it can be accommodated by management demand options.

In the water sector, there are co-benefits and trade-offs of adaptation with mitigation. For example, actions to reduce demand will typically use less energy than developing new resources. Since the processes involved in supplying, treating, delivering, collecting and then treating again water take energy, less water consumption implies less energy used, reducing the carbon footprint of the water industry and other abstractors. Research on energy and carbon footprint of water in households (that account for 89% of CO2 emissions in the water sector) shows that simple demand management measures, particularly those that reduce the amount of hot water used in the home, have huge potential to reduce the carbon footprint of water supply, use and disposal (Environment Agency 2008).

There are also a range of options associated with water quality. We do not consider these in detail here but note that these are generally a combination of hard and soft

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[48] For example, the feasibility of large infrastructure projects such as the building of a reservoir is limited by the availability of adequate land, and limitations imposed by the planning authorities.

[49] Average incremental social cost is obtained by dividing the net present value of the scheme costs by its discounted contribution to balancing supply-demand

infrastructure measures and that the soft (or natural) infrastructure options can have significant co-benefits with ecosystems (Section C.4).

C.3. The UK Food Sector

C.3.i. The Risk Landscape

Current vulnerability of the UK food sector*:* The food sector includes agriculture, but also a range of private and public actors involved in the manufacture, distribution and provision of food to people and organisations across the UK. It is the biggest manufacturing sector in the UK, accounting for 7% of the GDP, and employing a total of 3.7 million people across the various stages of production and supply, from farms to retail (DEFRA 2010). The UK produces around half of all the food consumed locally (with fruit and vegetables accounting for around 60% of imports). In 2006, it imported £24.8 billion and exported £10.5 billion. The UK is a major food producer (Table C3.1); agricultural productivity is high compared to the EU average but lower than that one for USA and France.

	UK	Euro Area	OECD (high income)	World	USA	France
Agricultural land (% of land area)	70	47	38	38	45	54
Agricultural productivity (value added per worker, 2000 $)	27701	22860	27680	939	47463	47153
Food production index (1999–2001 = 100)	98	98	102	111	105	98

Table C3.1. Food and agriculture key statistics. Source: World Bank 2009, World Development Indicators, Washington DC: World Bank

The food sector is susceptible to both local and global risk drivers. For instance, during the food crisis in 2007-2008, the UK showed all-in-all a high level of resilience, as food prices did not affect well-being substantially. This was partly due to the fact that the sources of food imports are very diverse. Food retailers are able to switch sources of supply rapidly in case of disruption (Defra 2009). Currently no single country accounts for more than 13% of UK food and drink food imports (Defra 2008). However, increases in food prices hit the poorest hardest. In 2006, an average of 8.9% of UK household expenditure was spent on food, rising slightly to 9.2% in 2007. But the poorest 10% allocated 15% of household expenditure to food in 2006 and therefore were particularly affected by rises in the cost of basic foodstuffs such as milk, bread and eggs, which have risen in price by far more than the average for the shopping basket as a whole[50].

Agricultural production is also highly sensitive to local climate variability, in particular, climate-related shocks. For example, the 2003 heat wave and the consecutive drought affected beet crops in the Midlands and autumn sown crops (e.g., oilseed rape failed to establish). During the 1995-1997 droughts agricultural losses amounted £180 million, particularly to livestock farming, and reduced yields for root crops and vegetables, while in the case of some arable crops there was an increase in yields (Cole and Marsh 2006). The 2007 summer floods destroyed large areas of crops. Other types of shocks, such as pests and diseases, are of equal (if not higher) importance to climate-related shocks.

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[50] Cabinet Office, Food Matters: Towards a Strategy for *the 21st Century* (Cabinet Office Strategy Unit, London, 2008).

Local drivers of changing risks: Agriculture in the UK is likely to be influenced by climate change; in particular, changing local levels of temperatures and precipitation (mean levels and extremes). Studies suggest that the balance of impacts of these changes is likely to be positive, with increased yields for many types of crops. The impacts are likely to vary geographically. AEA (2007) divides the UK into two agro-climatic zones: the North Atlantic (Ireland and Scotland) and the Central Atlantic (England and Wales). Both zones could see an increase in optimal farming conditions, and improvements livestock productivity. Agricultural productivity is also likely to be impacted by changes to ecosystems due to climate change (including pollinators, pests and diseases); increased water logging and reduced water quality associated with increased winter precipitation; and changes in flood risk and frequency of droughts. Some of these changes are summarised in Table C3.2. The impacts seen by individual farmers will depend on their geographic location, soil type, slope and local farming systems (Farming Futures, 2010). In coastal regions, sea level rise could lead to inundation and saline intrusion of some agricultural lands.

Impact	Opportunity	Challenge
Arable crop yields and distribution	- Increased winter wheat yield due to higher temperatures - Possible yield increase due to more CO2 available for growth - Earlier spring growth and ripening enabling earlier harvesting - Northern and western regions may become more suitable for some arable crops - New crops may become suitable to grow e.g. Durum wheat - Higher altitudes may be able to support arable crops	- Drought events could make yields less predictable - Prolonged periods of temperatures at 25°C+ during flowering could reduce yields. - More nitrogen and water required for higher yields and greater canopy cover - Although frosts will become less common, crops may experience more damage from rare frosts due to lack of acclimatisation - Possible soil erosion from torrential rainfall and saturation. - Warmer winters and reduced frosts weaken vernalisation required to initiate or accelerate flowering, affecting yields - Lower soil moisture may reduce germination in some crops - Wetter winters/autumns affect cultivation, sowing and harvesting timings
Livestock Conditions	-Forage crop productivity may be increase. -New breeds could be introduced e.g. hair sheep -New market opportunities may emerge for new species e.g. ostrich meat. -Housing needs can be reassessed due to altered lambing and calving to fit with grass growth patterns -Finishing systems may need to be changed to fit the climate	-Increased variability in grazing regimes due to wetter soil in autumn/winter -Less grass forage available due to drought, impacting on the volume of second silage cuts. - Increased CO2 may enhance primary production, but could lead to changes in leaf/sheaf ratio. - reduced nitrogen and increased fibre content in plants. This reduces feed quality and digestibility, and limits live weight gain - Prolonged dry weather may increase the need to supplement forage with bought-in feed, silage or forage, potentially increasing feed costs - Changes in global feed markets may affect costs

Table C3.2: Impacts of climate change on UK agriculture. Sources: Atkinson et al., 2005; Farming Futures, Focus on arable crops, fact sheet 10; Farming Futures, Focus on livestock, fact sheet 5.

There is evidence that farmers are less well equipped today to deal with long-term changes in environmental conditions than in earlier decades. For example, between the

60s and 90s the UK food sector had in place a set of efficient mechanisms that allowed it to sustain high productivity increases and adapt to changing climatic conditions. The system was supported by three elements: (i) high level of technological research, heavily funded by the public sector; (ii) A communication administration system which provided farmers with up to date information to take on-time decisions; (iii) a set of incentives that allowed economically efficient decisions. These three elements have gradually disappeared as the public sector involvement in agriculture has declined[51].

The UK food sector may also be affected by changes not linked with climate change impacts. For example, any changes in market conditions associated with changes to subsidies or incentives; new technologies; changes in consumer behaviour and diets[52] and changing pressures for alternative land uses. Climate change mitigation may also impact the agricultural sector through various pathways:

- **The need to constrain greenhouse gas emissions:** A northward and upward (i.e. to higher altitudes) shift in agriculture could increase emissions from the sector as the cultivation of previously undisturbed carbon-rich soils releases large amounts of greenhouse gases. Constraints on national emissions could lead to a shift towards lower intensity agriculture (nitrogen use efficiency or reduced cultivation). The sector could also be impacted by the need to reduce emissions in the food processing, retail and distribution (including, 'food miles' from imports) components associated with energy use and transport.
- **Increased demand for biofuels and biomass:** Recently there has been growing interest in technologies such as anaerobic digestion[53]. The development of bio-energies in general will likely reduce the amount of land available for food production. The likelihood and scale of such a displacement is uncertain. In generally, the effects of such a shift are likely to be largely reversible; productivity would shift back to food were the economic incentives reversed.

The others drivers of agricultural changes identified, may in some cases negatively affect the adaptive capacity of the UK food sector, creating barriers to adaptation. An example here is potential price distortions created by agricultural subsidies. Conversion of agricultural lands to other uses in response to other drivers could also limit potential future growth in the sector, if those conversions were irreversible.

The changing global food sector: The UK food sector will be affected by changes in global agricultural systems, through changing prices of foods. Globally, production and productivity will need to increase to meet the needs of a growing global population. Diets are also changing, with increasing demands for meat which will in turn result in more demand for land putting more stress on natural resources. These trends have a relatively low uncertainty. In the longer term, climate change will alter patterns of productivity globally, in ways that are difficult to predict. Owing to climate change and growing population, food prices are expected to be higher and more volatile in the long run. Global projections suggest that rising temperatures, altered rainfall patterns and more frequent extreme events will increasingly affect crop productions, often in those places that are already most vulnerable. With the potential for increased agricultural productivity in the UK, resulting from more favourable growing conditions, there is opportunity for exports of foods to increase.

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[51] For a discussion about the effects of a decline in government funded R&D and extension in agriculture in the UK see Thirtle(2004).

[52] E.g. a reduction in saturated fat consumption would have a small effect on livestock commodity consumption.

[53] Anaerobic digestion, popularly known as 'AD', is the controlled break down of organic matter in the absence of air to produce a combustible biogas and nutrient rich organic by-product.

Other risks associated with the food sector: Changes in agricultural practices and land conversion also impact other sectors, in particular, ecosystems, water quality and flood risk. For example, land clearing can lead to drier soils and increased diffuse pollution of water supplies. It can also increase levels of surface runoff and flood risks. Draining moorland and wetlands, and converting permanent pasture to arable land increases run-off and can create water quality problems.

C.3.ii. Key Evaluation Criteria for Decisions

The main actors involved in the food sector are: the private sector; the government (UK and EU); and non-governmental organisations[54]. Farmers, distributers and retailers constitute the private actors. For this group the key criterion in decision-making is short-term profitability.

The government plays a role in supporting the agricultural sector, securing food availability and in ensuring food safety and standards. More than 90% of legislation is set a European level, with local authorities responsible for monitoring and enforcement. The European Union regulates the agricultural sector through the *Common Agricultural Policy (CAP),* which is a system of agricultural subsidies and programmes, whose aim is to provide farmers with a reasonable standard of living, consumers with quality food at fair prices and to preserve rural heritage. For example, in England, the *single payment scheme* or *single farm payment* provides a single flat rate payment for maintaining land in cultivatable condition. The single farm payment is linked to meeting environmental, public, plant health and animal welfare standards and the need to keep land in good agricultural and environmental condition. Others policies also play a role in, for example, correcting market failures, food standards, and safeguarding social equity. At an international level, trade follows recognised standards, codes and guidelines, governed through a number of multilateral institutions.

C.3.iii. Adaptation Options

There are a range of options available to the UK food sector to maximise production and resilience to potential domestic and global shocks. These include many autonomous, reactive measures, such as shifting crop varieties and changing (shifting or enlarging) cultivation areas, which farmers already utilise to maximise profits in response to observed climate variability or changing food prices. Here, we focus on planned adaptation measures (including both public and private actions) that aim to increase the long-term resilience and productivity of the sector. These can be divided into two categories: 'no-regrets' options and 'tough choices'.

'No regrets' adaptation: The range of 'no-regret' adaptation options aims to increase the ability of the agriculture sector to cope with different future scenarios and without compromising future flexibility (within the food sector or in other sectors, in particular, water, ecosystems and flooding). They are beneficial with current climate variability and likely to become more beneficial with climate change. These types of options typically involve: small-scale engineering work that provides higher efficiency at relatively low cost; soft interventions (i.e. those that are necessary to ensure an adequate policy framework); the transfer of knowledge where and when it is most needed; and the research in technology that will help improve climate resilience. Examples include (e.g. Macgregor (2010) and others):

National/regional level:

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[54] Particularly involved in lobbying on issues of health, environment, animal welfare, living standards etc.

- Investing in skills, knowledge and technology: training, information provision and education and building long-term research capability (e.g. developing new crop varieties)
- Building broader sustainability: e.g. incentivising protection of ecosystems (maintaining high water tables), reducing soil erosion and water pollution, manage fertiliser and pesticide use, and flood control (e.g. reducing and slowing runoff by planting trees).
- Rebuilding soil fertility

Farm-level:

- Maximising efficiency of water use
- Adopting measures to maintain and increase soil moisture (e.g. minimum tillage, use of manures, compost and mulches)
- Reducing vulnerability to weather by creating semi-natural buffers and planting trees

Tough choices: We define 'tough choices' as those that require upfront costs that are likely (but uncertain) to be balanced by benefits in the medium-term (typically considered 'low-regrets'), and those that require trade-offs between agricultural productivity and benefits in other sectors, such as ecosystems, flood control and pollution. Specific examples are listed below:

- **Investing in on-farm infrastructure**: Interventions include increase of water storage, blocking grips and gullies, irrigation technologies, building animal shelters and building additional manure storage.
- **More production vs. less land conversion**: Simply producing more food without heeding the environmental impacts of this choice will likely shift the problem of global food supplies towards future generations, without solving the problem. The trade off between increased food production in the short and medium run, and lower but sustainable production in the future needs to be carefully balanced. This involves assessing the productivity value of ecosystems on which agriculture currently relies; and understanding the flow of services between ecosystems such as forests and peat land, and farm land.
- **Biotechnologies**: The UK Government is currently looking at the scientific evidence in order to make informed decisions concerning developments in GM technology. Defra has set up a GMO research programme aiming at commissioning high quality research designed to underpin the risk assessment of GMOs and their use in the UK.
- **Rebuilding agricultural lands**: Under high climate change scenarios, the value of agricultural lands in the UK could increase as global food demands and prices rise. Flexibility for increased production could be achieved today by investing in large-scale rebuilding of soil fertility and also restricting the conversion of agricultural lands to irreversible land-uses (e.g. new developments). This type of option is associated with a significant opportunity cost.

Some of these options have obvious co-benefits with other sectors. Investing in water storage and new technologies could reduce demand for irrigation during the summer, contributing to a decrease in water demand, and reducing direct river abstractions that can potentially harm the river ecosystem. Rebuilding agricultural lands and restricting their conversion to irreversible land-uses will simultaneously address a wider range of climate change risks such as water shortages and floods and increased erosion and runoff. Increase food production using pesticides and fertilisers has to be carefully managed to reduce the existing pressure on the environment, and to avoid pollution, the risk of which can increase with projected changes in heavy rainfall.

Climate change	Impacts	Current Vulnerability	Tier 1 (direct) responses: Adaptation	Risk	Tier 2 responses: Optimization
UK: Higher temperatures, less winter frosts	Longer growing season, increased yields.	Lack of central planning in dealing with information, technology and incentives	**Higher production** **Shift in crops** **Increase in cultivated areas**	Land clearing Increase in fertilizers use Exacerbation of water stress in specific areas (e.g. SE)	**Zoning; ecosystem protection; incentives to efficient fertilizers use**
UK: Wetter winters and drier summers, changes in extremes.	Increased winter floods, increased summer droughts and water stress	Medium	**Information systems; research on more resistant crops; on-farm engineering and infrastructure**	Land clearing Increase in fertilizers use Exacerbation of water stress in specific areas (e.g. SE).	**Creation of appropriate structures**
Global: Climate change impacts on other regions of the world	Shocks on global food chain	Good			

Table C3.3: Summary of climate change impacts and response options

C.4. Ecosystems and Biodiversity in the UK

Contributed by Alice Hardiman, the Royal Society for the Protection of Birds, *in collaboration with the team at LSE*

It is important to note upfront that there are two elements of ecosystems that may require adaptation. The first is ecosystems for the purpose of ecosystem services, including tangible services, such as water and air quality regulation and recreation, as well as intangible services, such as aesthetic enjoyment. The second is biodiversity, the living component of ecosystems including terrestrial and aquatic organisms. Adaptation options that aim to protect or utilise ecosystem services can have benefits in terms of protecting biodiversity, but this is not always the case. In some circumstances, separate options may be required if the goal of adaptation is to protect biodiversity alone.

C.4.i. The Risk Landscape

Current vulnerability: levels of biodiversity (see box) in the UK have declined significantly in the past as a result of long-term stresses. For example, many indicators show long term deterioration in the populations of many species, including: farmland and woodland birds, specialist butterflies, bats; as well as plant diversity (in woodlands, grasslands and boundary habitats) (JNCC 2009). Many of these declines have slowed since 2000 as a result of stronger regulation and conservation activities.

Ecosystems are also vulnerable to short-term shocks, such as extreme weather events. For example, the tidal surge on the east coast of England in November 2007 caused widespread inundation of freshwater habitat by salt water, and not all such areas will return to their former freshwater state. In woodlands, drought has been shown to cause change in tree composition (Peterken & Mountford 1996). While ecosystems have always been exposed to extreme events, human actions, such as land-use changes (which can restrict mobility of species) and flood defences can increase vulnerability (see B.2.i for flood-related impacts).

There is evidence to show that climate change is already having observable effects on ecosystems and levels of biodiversity:

- **Species' ranges have shifted** for a wide range of taxa, including migratory species and those at both the northern and southern extremes of their range in the UK (Austin & Rehfisch 2005, Warren et al. 2001, Franco 2006). However, some species have not spread as expected (Hickling 2005, 2006).
- **Seasonal events in spring and summer are occurring earlier**. For example first leafing dates of trees (oak leafing has advanced three weeks in the last 50 years), egg-laying dates of birds, first spawning of amphibians and earlier fruiting of species such as blackberry (Beebee 1995, Crick & Sparks 1999, Sparks et al. 1997, Woiwood 1997). Recent evidence shows differential phenological change among trophic levels in ecosystems, heightening the potential risk of temporal mismatch in key interactions (Thackeray et al. 2010)
- **Rising temperatures** have lead to changes in habitat preferences of some species, mirroring traditional behaviour in warmer regions.
- **Sea-level rise** has already led to loss of some intertidal habitat; for example, the low-lying coasts of south-east England, where significant losses of saltmarsh have been recorded from 12 Special Protection Areas (Royal Haskoning 2006).

Definitions:

Biodiversity: The International Union for Conservation of Nature defines biodiversity as *'the variability among living organisms from all sources including terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems'.* Biodiversity forms the living component of ecosystems, which in turn provide benefits for people, often referred to as ecosystem services.

E**cosystems:** The Millennium Ecosystem Assessment defines an ecosystem as *'A dynamic complex of plant, animal, and microorganism communities and their non-living environment interacting as a functional unit'.*

Ecosystem services: The tangible services provided by ecosystems to the economy and society, such as water quality regulation, air quality regulation, disease management, recreation, tourism and local climate regulation, as well as more intangible services, such as aesthetic enjoyment and well-being.

Other related risks: Ecosystems provide a wide range of services to human society, including air and water purification, food, regulation of regional and local climate, fresh water, natural hazard risk reduction (e.g. flood control), maintaining soil fertility and pest management. Degradation of ecosystems could mean the reduced effectiveness, or complete loss, of these services. The Millennium Ecosystem Assessment estimates that globally, approximately 60% (15 out of 24) of the *ecosystem services* are being degraded or used unsustainably, including fresh water, capture fisheries, air and water purification, and the regulation of regional and local climate, natural hazards, and pests. The full costs of the loss and degradation of these ecosystem services are difficult to measure, but the available evidence demonstrates that they are substantial and growing.

Drivers of future risk: Climate change and non-climate drivers of future risk will differentially affect biodiversity and ecosystems across the UK and over time. At a national level, there is no one dominant driver of risk. Climate change, through its direct and indirect impacts, is the dominant driver of long-term uncertainty[55]. Natural England's 2008 *State of the Natural Environment report* summarised the major social, technological, environmental, economic and political drivers of change as:

- **Invasive species and diseases** can have significant effects upon the natural environment, affecting the existence or integrity of some species and habitats.
- **Land-use change:** current changes in the use of land and sea present both threats and opportunities to the natural environment. Major drivers of change include energy generation (including new alternative renewable sources) and the growing demands for water.
- **Management of land, sea and freshwater.** Eighty percent of the land area of England is managed either for agriculture or forestry. Much land use is intensive and specialised; which can lead to ecosystem loss. However, well managed uses need not damage ecosystems, even where intensive. For some areas, neglect rather than intensification, impacts on the environment. Marine ecosystems have been significantly impacted by intensive commercial fishing.
- **Pollution**. Pollution presents a wide range of pressures and risks to the natural environment, particularly through nutrient enrichment and toxic chemicals. Nutrient enrichment, arising from diffuse or specific point sources, can lead to excessive growth of plant life in aquatic and terrestrial habitats, adversely affecting species and ecosystems. The toxic chemicals that enter the natural environment on a daily basis include pesticides, herbicides and veterinary medicines, and industrial and other chemicals.
- **Climatic changes**. Changing mean climate and intensification of extremes are likely to lead to degradation of ecosystems. For example, if current patterns and rates of phenological change are indicative of future trends, warming may exacerbate trophic mismatching, further disrupting the functioning, persistence and resilience of many ecosystems[15].The current observed impact of climate change, alongside modelling studies, suggests a high susceptibility of ecosystems to even small changes in climate. Impacts are likely to intensify non-linearly with global mean temperatures. Climate change could also aggravate other drivers; through for example, water quality impacts and increasing the ranges of invasive species and diseases. Land management actions associated with **adaptation and mitigation** also have the potential to lead to significant degradation of ecosystems (see discussions related to flooding, water and agriculture).

Given past evidence, the sensitivity to these drivers could be high. Many species adapt autonomously by relocating to habitats with more suitable climate conditions. However, human systems can often limit adaptive capacity, for example, by removing natural migration routes.

Risk of irreversible outcomes: Species extinction and losses of ecosystem services are irreversible impacts. Projections of shifts in suitable climatic conditions (Huntley et al. 2007, Walmsley et al. 2007) for a range of taxa show significant risk of local extinction of UK species. Globally, predictions of extinction risk suggest as many as 35% of species studied may be 'committed to extinction' under a high climate change scenario (Thomas et al. 2004). Some species' extinctions may directly affect ecosystem function and thereby the provision of ecosystem services. In some studies, increased species richness is associated with improved ecosystem service provision, for example by reducing variability in ecological processes through the insurance effect, buffering the ecosystem

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[55] Uncertainty stems from a combination of climate projections, uncertainty over individual species response, the impact of individual species changes on ecosystems, the effect of human responses to climate change.

and so the services it provides as conditions fluctuate (Yachi & Loreau 1999, Dang et al. 2005, Cottingham et al. 2001).

C.4.ii. Key Evaluation Criteria for Decisions

Valuation of ecosystems: Of all the sectors explored, ecosystems and biodiversity involve the most challenging criteria for decision-making in that the benefits of adaptation have significant non-monetary components that are dependent on social and ethical preferences. There are broadly two strands to valuation of ecosystems (see Box for details). The first values the services provided by ecosystems; in general these valuations of ecosystem services are not comprehensive. The second (complementary) approach, reflects ethical and social preferences by valuing ecosystems and biodiversity in their own right and reflects these values through non-economic frameworks such as legislation.

Treatment of irreversibility: Another important decision factor linked with valuation of ecosystems is how to treat the irreversibility of impacts on biodiversity. Climate change, as well as other pressures, could lead to the permanent loss of some species from the UK, and potentially even extinction. The implications of this for decision-making will again depend on ethical and social judgements. In a Europe-wide survey, 90% of UK respondents agreed that halting biodiversity loss is a moral obligation because we have a "*responsibility as stewards of nature*" (Flash Eurobarometer survey, 2007).

Valuation of Ecosystems:

The Millennium Ecosystem Assessment (MEA) identified four sources of value related to ecosystems, which in total comprise the Total Economic Value (TEV):

- **Direct use values**, including the benefits we get from e.g. food, timber or reaction
- **Indirect use values**, which include the processes that contribute to the production of goods and services like soil formation, water purification and pollination.
- **Non-use values**: well-being associated with simply knowing that a resource exists or because they wish to bequeath it to future generations.
- **Options values**: value in preserving the option of use in the future.

Environmental economists utilise a range of tools to assess each of these values. The MEA concluded that the TEV of a system will always underestimate the Total Systems Value because for practical reasons only a subset of services can be valued; for example, it cannot capture the full systemic value associated with underpinning life support systems.

Ascertaining economic non-use values associated with biodiversity itself is not straightforward, but a variety of contingent valuation methods do exist. In 2004, a Defra funded study (Christie et al. 2004) found that the public is willing to make significant payments for policies which preserve or enhance biodiversity in their regions (for example, the results indicate a willingness to pay an annual tax of between £37-£70 p.a. specifically for biodiversity projects).

The UK National Ecosystem Assessment will be the first analysis of the UK's natural environment in terms of the benefits it provides to society and continuing economic prosperity. The assessment began in mid-2009 and will report in early 2011.

Current policy context: Biodiversity and ecosystems are protected by both UK and EU legislation. For example, European Directives underpin the designation of the UK's internationally important sites for biodiversity, protecting them from adverse effects, and aim to ensure 'good ecological status' of UK water[56]. National legislation underpins a network of Sites of Special Scientific Interest, notified for their biological or geological

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[56] The Birds, Habitats and Water Framework Directives.

value and protected from development and most adverse land use change. In addition, the UK Government has committed to two important international targets to protect biodiversity: firstly, in 2001, European Union Heads of State or Government agreed that biodiversity decline should be halted with the aim of reaching this objective by 2010[57]; secondly, in 2002, Heads of State at the United Nations World Summit on Sustainable Development committed themselves to achieve, by 2010, a significant reduction of the current rate of biodiversity loss at the global, regional and national level, as a *"contribution to poverty alleviation and to the benefit of all life on Earth"*[58] Each of these policies are based on ecological (defined by social and ethical preferences) rather than economic criteria, so valuation has played no explicit role.

Non-governmental organisations such as the RSPB, the Wildlife Trust, the National Trust and many others also play an important role in protecting biodiversity and ecosystems in the UK through their ownership and management of land. For example, the RSPB manages 206 nature reserves covering 142,044 hectares.

Recently, economic valuation of ecosystem services has played a more important role in decision-making, particularly in flood and water management. For example, managed coastal realignment, where coasts are freed to return to their natural state by the realignment of defences, frequently represents a cost-effective solution to coastal flood defence. In one example, realignment at Freiston Shore in Lincolnshire had a higher net present value than maintaining hard flood defences, without even taking into account the significant environmental benefits gained from providing another 65ha of intertidal habitat. The Pitt Review also made several recommendations highlighting the benefits of 'working with natural processes, in flood and water supply management.

C.4.iii. Adaptation Options

Species have inherent autonomous adaptive capacity. For example, we have observed that, where they are able to, species will move inline with their climatically suitable conditions, or alter their lifecycles and habitat choices. Some species (those with rapid reproduction) could also evolve to meet new conditions. However, autonomous adaptive capacity is constrained in many cases by natural or human barriers, related to for example, their existing conservation status and the highly human-modified landscape of the UK. Adaptive capacity will also be limited by the rate of climatic change and its level (Huntley 2007); that is, the faster and larger the climatic change, the less time to respond (and the greater the response required).

Human interventions would be required to support the adaptation of biodiversity and ecosystems in the UK to climate change by overcoming barriers to autonomous adaptation. Options to facilitate autonomous adaptation include for example (adapted from Hopkins et al. 2007):

- **Improve monitoring and information to enable evidence-based decisions:** lack of information is a significant barrier to adaptation.
- **Conserve existing protected areas and other high-quality habitats**: these areas are important in the short-term as they support vulnerable species and habitats, and in the longer-term because they maintain a wide range and variability of underlying environmental conditions now rare in the wider countryside that are likely to be important for biodiversity under any future scenario.

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[57] See www.ec.europa.eu/environment/nature

[58] See www.un.org/esa/sustdev/sdissues/biodiversity/biod.htm

- **Reduce sources of harm not linked to climate.** For example, stronger regulatory standards related to land-use change, improved land-management and controls on invasive species.
- **Developing ecologically resilient and varied landscapes.** Autonomous adaptation will be enabled by ensuring landscapes remain varied (to provide microrefugia for species as climatic conditions change, and increase alternative habitats for species shifting their distribution from less-hospitable areas) and allowing space for natural physical processes to take place (e.g. by allowing natural processes of change to take place, such as erosion and deposition, there is increased potential for species to adapt naturally to changes).
- **Establishing ecological networks through habitat protection, restoration and creation.** Creating new habitat, restoring degraded habitat, or reducing the intensity of management of some areas will provide natural pathways to encourage species to move to more hospitable areas.

There has been little work to date to assess the costs of these options at a national level, the closest being a study in 2006 that assessed the cost of delivering the UK Biodiversity Action Plan (purely related to conserving existing protected areas and high-quality habitats) as £677 million per year (GHK and RPS Ecology 2006). Each of these options will provide benefits under any future scenario and therefore, could be considered 'no-regrets'. The benefit relative to cost will vary significantly on a case-by-case basis. Each can be implemented today and will provide immediate benefits. However, a good decision-making process will take account of the fact that it can take several years to create or rebuild a habitat that can support a strong and biodiverse ecosystem. For example, a native pinewood in Scotland might take 60-years or more to mature, whereas as species-rich grassland will require around 5 years.

Ecosystems can also provide adaptation solutions for other sectors through the services they provide. Ecosystem-based adaptation solutions have been considered in each of the other sector case studies.

Under more extreme scenarios of climate change, assisted colonisation is proposed by some to be the only option to conserve some species. These initiatives entail large-scale transfers of species outside their natural ranges (Hoegh-Guldberg et al. 2008). However, the risks associated with such initiatives are high; there is potential to produce unintended and unpredictable impacts. The impacts of introduced species vary over time and space under the influence of local environmental variables, interactions between species and evolutionary change. Some potential impacts, such as native species extinctions, are large and irreversible (Ricciardi and Simberloff 2008).

C.5. Summary of Adaptation Options by Sector

FLOODING IN THE UK										
Adaptation Option	**Summary Characteristics**	**Geographical Constraints**	**Relative Economic Costs**	**Relative Economic Benefits**	**Common Co-benefits**	**Common Trade-offs**	**Lifetime (lead-time, turnover)**	**Flexibility & Sunk-costs**	**Distribution of Costs and Benefits**	**Risks**
Hard barriers and other infrastructure (including flood wall, embankment, hard flood storage)	Anticipatory; complement		High (~£0.5 – 4 m per km embankments and sea walls)	Potentially High		Potential damage to ecosystems and visual appearance; downstream risks	Long (20-100 years); long lead-time for large projects	High sunk-costs but can incorporate flexibility	Typically taxpayer funded, local benefits	Small risk of failure; larger if not maintained
Enhanced 'hard' drainage and sewerage systems	Anticipatory; complement	Typically urban	High if early capital replacement; low if in line with turnover	Potentially High			Long (100 years)	High sunk-costs, can incorporate flexibility	Typically taxpayer funded, local benefits	Risk of failure if not maintained
Managed realignment/retreat	Anticipatory; typically substitute	Typically coasts and more rural areas	Medium to High (e.g. £1 – 40m with environmental restoration)	Potentially High	Restoration of natural habitats and ecosystems	Possibly sacrificing some land or property			Typically taxpayer funded, local benefits	
Risk-averse planning of new developments	Anticipatory; complement	Relevant in flood exposed regions	Low *(but potential high costs if build in exposed regions)*	Potentially High		Potential trade-offs with development objectives	Long		Policy	None *(but risk if build in exposed regions)*
Large-scale 'Soft' Infrastructure (natural barriers, natural flood storage, enhanced soil conditions)	Anticipatory; typically complement	Requires large land areas for natural ecosystems	Medium (£10-100k small-scale wetland and channel restoration; £1 - 10 million major channel restoration, flood storage, floodplain reconnection)	Medium (uncertain, potentially high local benefits)	Ecosystems and associated benefits	Other land uses; downstream risks	Medium	Lower sunk-costs	Local benefits; range of possible funders (e.g. local community, charities)	Potentially higher risk of failure and more uncertain benefits than hard infrastructure
Urban 'soft' infrastructure (green	Anticipatory; typically	Typically urban	Medium (Green roofs -	Uncertain	Ecosystems; cooling and		Medium	Lower sunk-costs	Local benefits; range of	Potentially higher risk of

roofs and permeable pavements)	complement		additional £10-20 per sqft; surface solutions ~£100-200k per small-scale project)		insulation of urban areas and buildings				possible funders (e.g. local community, charities)	failure and more uncertain benefits than hard infrastructure
Property-level resistance and resilience measures (retrofit or new build; voluntary or implemented through building regulations)	Anticipatory; typically complement	More feasible for new build or during refurbishment	Low-High £100 - £40,000 (retrofit, depending on scale, e.g. >£20,000 structural changes e.g. foundations; cheaper for new build)	Typically payback after one event. E.g. Resistance measures are cost-effective for properties with annual chance of flooding >2%.			Long	Low to High sunk-costs; potential for flexibility	Individual benefits	Low risk if well maintained; more uncertain benefits
Temporary barriers (including demountable defences and sand bags)	Reactive; typically complement	Limited suitability	Low-Medium; labour intensive	Low to Medium; ok for some shocks but not economic if permanent			Temporary	Low sunk-costs and flexible	Individual benefits; usually community or individual	High risk of failure
Temporary property-level measures (e.g. flood boards, air-brick covers)	Reactive; typically complement		Low (e.g. <£100 airbrick covers; 1000+ for boards etc)	Medium			Temporary	Low sunk-costs and flexible	Individual	High; but lower risk of failure than sandbags
Disaster response planning (e.g. evacuation procedures and emergency services)	Anticipatory; typically complement			High	Components can benefits all disasters				Taxpayer funded; all benefit	Some risk of failure
Risk information and early warning systems	Anticipatory; typically complement			High					Taxpayer funded; all benefit	Some risk of failure

THE UK FOOD SECTOR

Adaptation Option	Summary Characteristics	Geographical Constraints	Relative Economic Costs	Relative Economic Benefits	Common Co-benefits	Common Trade-offs	Lifetime	Flexibility & Sunk-costs	Distribution of Costs and Benefits	Risks
Training and technical assistance for adaptation	Anticipatory; complementary		Low	Potentially High					Many sources of possible funding; farmer benefits	
Information services, inc. weather forecasting and early warning systems	Anticipatory; complementary		Low	Potentially High	Benefits many weather-exposed sectors				Typically taxpayer funded; all benefit	Some risk of failure
Research and Development	Anticipatory; complementary		Medium	Potentially High					Many sources of possible funding; global benefits	
Changing varieties (arable/livestock), timing and land-use	Reactive/ Anticipatory; complementary	Expand land if available	Low-Medium	Potentially High			Short (1-5 years)	Low sunk-costs	Individual Farmer; consumer benefit	Low
Natural environment solution to building soil fertility and resilience to climate; semi-natural buffers and barriers	Anticipatory; complementary		Low-Medium	Medium	Ecosystem protection; potential for soil fertility, flood control and improved water quality	Potentially some near-term production	Short-medium	Low sunk-costs	Individual Farmer; consumer benefit	Low
Alter farming methods to reduce soil erosion, mange soil moisture and improve soil fertility	Anticipatory; complementary		Low	Potentially High	Building soil fertility and reducing water pollution; potential to reduce fertiliser use	Potentially some near-term production	Short	Low sunk-costs	Individual Farmer; consumer benefit	Low
Alter farming methods to improve efficient water use	Anticipatory; complementary		Low	Medium	Reduced water stress; reduced costs	Potentially some near-term production	Short		Individual Farmer	Low
On-farm infrastructure: water storage; blocking gullies; irrigation; animal shelters; manure storage etc.	Anticipatory; complementary		High	High		Irrigation may increase water stress	Medium	Some sunk-costs	Individual Farmer	Low
Plant technologies; e.g. biotechnology	Anticipatory /reactive; complementary		Medium-High	Medium-High		Potential damages to local	Short	Medium-High sunk-costs	Individual Farmer; consumer	Low – Medium: new

						ecosystems in some cases			benefit	technology
Anticipatory extension of agricultural lands / preventing conversion to other land-use	Anticipatory; complementary	Expand if land available	Potentially High (opportunity cost)	Potentially High. but uncertain		Other land-uses	Short	Low sunk-costs, high flexibility	Many sources of possible funding; food security benefit	

THE UK WATER SECTOR

Adaptation Option	**Summary Characteristics**	**Geographical Constraints**	**Relative Economic Costs**	**Relative Economic Benefits**	**Common Co-benefits**	**Common Trade-offs**	**Lifetime (lead-time, turnover)**	**Flexibility & Sunk-costs**	**Distribution of Costs and Benefits**	**Risks**
<u>Supply-based</u>										
New reservoir	Anticipatory; complement	Requires large space and public consent	High	Potentially High	Amenity and recreation; some habitat provision	Impact on environment; high energy requirements	Long (100 years), with long lead time (15 – 20 years)	High sunk-cost; flexibility can be incorporated	Water companies and consumers	Low - Medium (may fail under extreme droughts)
Enlarged reservoir	Anticipatory; complement	If existing reservoir is suitable	Medium-High	Potentially High		Impact on environment; high energy requirements	Long (100 years), with medium lead time (5 – 10 years)	High sunk-cost	Water companies and consumers	Low - Medium (may fail under extreme droughts)
Farm-based winter storage	Anticipatory; complement or substitute to river abstraction	Available storage sites	Low	Potentially High	Reduced impact of river abstractions		Short-Medium (short lead time)	Medium sunk-costs	Local users; agricultural users	Low - Medium (may fail under extreme droughts)
Bulk water transfers: within region or from outside by canal, pipeline or river	Anticipatory; complement	Only possible in some catchments	Low (river) – Medium (pipes and canal)	Low (river and canal) – Medium (pipes)			Medium (30 years); 3 – 10 yr lead time	Medium sunk-costs; low flexibility in pipelines	Water companies and consumers	Low - Medium
Waste-water re-use	Complementary; anticipatory or reactive		Low – High (depending on type)	Uncertain			30 years; lead time 3 – 5 years	Low sunk-costs; potential for flexibility	Water companies and consumers	
Aquifer storage and	Anticipatory or	Must have	Medium	Potentially		Energy	15 – 30	High sunk-	Water	Low

recovery	reactive ; complement	aquifer close to resource zone		High		intensive	years; 5 – 10 year lead time	costs; potential for flexibility	companies and consumers	
Desalination	Anticipatory; complement	Close to sea	Low-High	Potential High		Energy intensive	Long; short to long lead time	High sunk-cost	Water companies and consumers	Low
New or enhancement of existing groundwater source	Anticipatory or reactive ; complement	Close to a suitable source	Medium	Medium		Medium energy use	Up to 30 years; short lead time	Low sunk-cost; potential for flexibility	Water companies and consumers	Medium (medium resilience to climate)
New direct river abstraction	Anticipatory or reactive ; complement	Close to a suitable source	Low	Medium		Impacts on ecosystems; medium energy use	Up to 30 years; short lead time	Low sunk-cost; potential for flexibility	Water companies and consumers	High (low resilience to climate)
<u>Demand-based</u>										
Reduced distribution leakage	Anticipatory or reactive; complement		Medium, Can be uneconomic below certain level	Potentially high			Long (1-5 yr lead time)	Low sunk-cost; potential for flexibility	Water companies and consumers	Low
Reduced supply pipe leakage (customer pipes: in England and Wales 25% of total leakage)	Anticipatory or reactive; complement		Can be uneconomic below certain level	No data			Long (1-5 yr lead time)	Low sunk-cost; potential for flexibility	Water companies and consumers	Low
Metering and tariff structures to promote more efficient use	Anticipatory; complement		140-160pence per cubic metre	Medium; but limits to effectiveness	Can reduce pipe leakage		Short (meters last around 10 years)	Low sunk-costs; saturates when all houses metered	Funded by water companies; consumer benefit	Low
Water efficiency equipment and fittings in new builds and refurbishment	Anticipatory; complement		Low	High	Reduced energy consumption		Short-Medium (10 – 15 years)	Low sunk-costs	Consumer	Low
License trading (transfer of supply licences between organisations)	Anticipatory; complement									
Public information and education to promote water conservation and efficient use	Anticipatory; complement		Low	Potentially high						
Managing new developments in catchment areas	Anticipatory; complement					Other development objectives				
Water re-use and recycling (e.g. rainwater harvesting,	Anticipatory or reactive;		Most cost-effective for	Potentially high	Co-benefits for		Medium (short lead	Low sunk-costs	Consumer	Low

grey-water recycling for non-drinking water).	complement		new buildings and when combined with metering		environment		time)			
Regulating water use	Reactive; complement		Low	Potential high						

ECOSYSTEMS AND BIODIVERSITY IN THE UK

Adaptation Option	Summary Characteristics	Geographical Constraints	Relative Economic Costs	Relative Economic Benefits	Common Co-benefits	Common Trade-offs	Lifetime (lead-time, turnover)	Flexibility & Sunk-costs	Distribution of Costs and Benefits	Risks
Improve monitoring and information to enable evidence-based decisions	Anticipatory; complementary; beneficial now and under any future scenario	Nationwide and must link to international systems	**Uncertain**	**uncertain**			Could take time to establish and then requires regular review (2 years, 5 years).	High sunk costs; enables flexible decision-making.		Low
Conserve existing protected areas and other high-quality habitats	Anticipatory; complementary; beneficial now and under any future scenario	Constrained by geology, soil, land use, and (for wetlands) water quality and availability.	**Uncertain**	**uncertain**	Provision of ecosystem services (depending on ecosystem and location with respect to people).	Conflicts with some land management or use change.	Already in place.	Low sunk costs (already in place); potentially flexible, but with significant negative consequences for biodiversity if overturned.	Different benefits distributed differently, e.g. existence value could be nationwide, amenity value highly localised.	Low
Reduce sources of harm not linked to climate	Anticipatory; complementary; beneficial now and under any future scenario	Nationwide, prioritising most vulnerable ecosystems and biodiversity	**Uncertain**	**uncertain**	Addressing pollution will benefit the water sector by improving raw water quality.	Where buffering sites is necessary, can conflict with some land management or use change.	Depends on source of harm.	High sunk costs in some cases, but existing legislative drivers (e.g. WFD) in place; flexible and enables future flexibility in land use and management,	Depends on source of harm, e.g. for diffuse pollution could be water companies and water customers benefiting from reduced water treatment costs.	Low
Developing ecologically resilient and varied landscapes	Anticipatory; complementary; beneficial now and under any future scenario	Constrained by land use and land management.	**uncertain**	**uncertain**	Potential benefits for flood risk management sector in	Conflicts with some land management or use.	Variable to establish depending on habitat, slow	Low sunk cost; flexible and enables future flexibility in	Different benefits distributed differently, e.g. existence	Low

					flood-prone catchments. Benefits for recreation, tourism, education and amenity.		turnover.	land use and management,	value could be nationwide, amenity value highly localised.	
Establishing ecological networks through habitat protection, restoration and creation.	Anticipatory; complementary; beneficial now and under any future scenario	Constrained by geology, soil, land use, and (for wetlands) water quality and availability.	**Uncertain**	**uncertain**	Benefits for recreation, tourism, education and amenity. Provision of ecosystem services depending on ecosystem and location with respect to people.	Conflicts with some land management or use.	Variable to establish depending on habitat, slow turnover.	Potentially high sunk costs; flexible, but with significant negative consequences for biodiversity if overturned.	Different benefits distributed differently, e.g. existence value could be nationwide, amenity value highly localised.	Low
Translocation within existing natural range	Reactive and complementary		**Uncertain**	**uncertain**	Potential benefits for recreation, amenity and tourism.		Long lead-in time.	High sunk costs; limited flexibility in some cases.	Different benefits distributed differently, e.g. existence value could be nationwide, amenity value highly localised.	Medium (reduced by careful investigation and planning).
Assisted colonisation	Reactive**.**		**Uncertain**	**uncertain**	Potential benefits for recreation, amenity and tourism.	Potential for significant negative ecological consequences.	Long lead-in time.	High sunk costs; limited flexibility in some cases.	Different benefits distributed differently, e.g. existence value could be nationwide, amenity value highly localised.	High.

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