Appendix D

Recommendations for further work

The investigations and analyses performed on the responses to increased flood risks have highlighted areas of inadequate knowledge and limitations in modelling capabilities. To reduce uncertainties and make more effective choices in long term flood management, we need first to improve our ability to understand the functioning of various response measures, interventions, and policies and, second, reduce uncertainties concerning their efficacy and sustainability.

This appendix presents recommendations for further work to address key issues and knowledge gaps concerning responses to future risks of flooding at the catchment/coastal and urban scales. Areas of research have been prioritised, based directly on the evidence gathered and practical insights gained during the work reported in this volume.

While the further work recommended here has been disaggregated into specific topics, to allow evidence-based prioritisation, stakeholder and advisory groups stressed that additional work in the social, economic, physical and engineering sciences would add most value through a co-ordinated national programme and within the framework of the holistic and integrated approach adopted in this Foresight project. If developed appropriately, the technique for strategic assessment of flood risks employed here could be used as a 'national test bed' to investigate the effects of new knowledge and technical advances in enhancing the reductions in flood risk that could be achieved using different responses. Such development must, throughout, involve end users and stakeholders. This would help to ensure that research findings are relevant to the needs of policy and decision makers.

The recommendations are presented under the headings of:

- Responses to future flood risk.
- Responses to coastal erosion.
- Strategic assessment of responses to future flood risk in the UK.
- Sustainability and governance of future flood-management responses.

Responses to future flood risk

Catchment and coastal-scale responses

In setting priorities for further work and future research in the study of catchment and coastal scale responses, the scores for flood-risk reduction and uncertainty analysis were used to identify responses possessing both a high potential to reduce flood risk and high uncertainty. For these responses, further research should reduce uncertainty concerning the technical, social, economic, governance and environmental aspects of their functioning and implementation with the potential to significantly improve our capability to manage future flood risk equitably and sustainably.

Research priorities for responses were prioritised using a research priority factor defined by:

$$RPF = UBW/FRR$$

where, RPF = research priority factor, UBW = mean uncertainty band width, and FRR = mean flood risk reduction score. The mean flood risk reduction and mean uncertainty band width for each response group were found by averaging the scores and band widths for the four scenarios in the 2080s. This was done so that research priorities are independent of the choice of future scenario (scenario-specific research priorities would diverge very significantly, and could be calculated if required). On this basis, the top ten response groups deserving priority for further research are listed in Table D.1 (note: where response groups were combined to reflect the fact that they could only be effective when implemented together, the combined response groups were scored rather than the individual groups themselves). The table also indicates the academic discipline(s) within which R&D work would reside.

A striking feature of Table D1 is the breadth of research involved in advancing knowledge on responses to future increases in flood risk. Prioritised research topics span a range of disciplines that fall into the domains of the Engineering and Physical Sciences Research Council, Natural Environment Research Council, Economic and Social Research Council, Biotechnical and Biological Research Council and the Arts and Humanities Research Council. As many responses are cross-disciplinary, further progress in understanding and modelling them will require that sponsors contribute to multi-disciplinary research projects and consortia.

Table D1 indicates the response groups prioritised for research, but does not list particular topics or issues requiring further research. Details may be found in Appendix A, as part of 'emerging issues' in the summary descriptions of the response groups. However, two topics of over-arching importance that merit specific mention here are:

- Investigations in representative rural-catchments are urgently required to establish the effectiveness of distributed storage and conveyance measures in reducing downstream flood risk, taking account of temporal variability of precipitation and spatial scale of the catchment.
- Research on River and Coastal Defences is required to develop a strategy for reducing the risk of infrastructure failure under extreme flood events.

Table D1 **Priorities for further work to reduce uncertainty in responses to catchment and coastal scale flooding**

Priority	Response Group	Disciplinary Area
1	Land use Planning and Management	Social Sciences
2	Floodproofing Buildings	Engineering and Physical Sciences
3	rural-catchment Storage	Natural Environment, Engineering and Physical Sciences
4	River Defences	Engineering and Physical Sciences
5	Rural Conveyance	Natural Environment
6	Individual Damage Avoidance Actions	Humanities and Social Sciences
7	Coastal Defences	Engineering and Physical Sciences
8	Real-time Flood Event Management	Social Sciences, Natural Environment, Engineering and Physical Sciences
9	Pre-event Measures	Social Sciences, Engineering and Physical Sciences
10	River Conveyance	Natural Environment, Engineering and Physical Sciences

Intra-urban responses

The same approach as for responses to catchment and coastal scale flooding was used to identify and prioritise further work on responses to intra-urban flood risk. On this basis, the priority order of responses in terms of meriting and requiring further research is listed in Table D.2.

The response groups achieving the highest priorities for further research relate to planning and managing urban spaces, and provision of above ground pathways in existing and new urban areas though creation of green corridors and flood routes. These priorities are linked to the need for better computer models of the flood defence assets in managing urban storm flows. For example, the ability of main drainage models to simulate system performance under the largest and most devastating storm events is unproven.

Table D2 **Priorities for further work to reduce uncertainty in intra-urban responses**

Priority	Response Group	Disciplinary Area
1	Urban area development, operation and form (including sacrificial areas)	Social Science, Engineering and Physical Sciences
2	Source control (plus above ground pathways)	Engineering and Physical Sciences
	Building development, operation and form	Engineering and Physical Sciences
3	Storage above and below ground	Engineering and Physical Sciences
4	Main drainage form, maintenance and operation	Engineering Sciences
5	Groundwater control	Natural Environment, Engineering and Physical Sciences

It is no coincidence that the intra-urban response group ranked first matches that in catchment and coastal-scale assessment, emphasising the crucial requirement for research on town and country planning to reduce flood risks. In the urban area, planning needs better to account for the diversity of constituent elements of urban surface form and type.

Responses that operate at the scale of the individual building and curtilage ranked second in the catchment scale assessment, and joint second in intra-urban list. In this response group, attention should focus on better representing the performance of building drainage and floodproofing as well as source control measures, including SUDS and integrated water management approaches, within integrated models of the urban drainage system. Development of flood risk assessments and response measures at individual property level will require more sophisticated models and improved topographical resolution to support continuous simulations. Runoff models must encompass both engineering and planning components of the flood control process for the intra-urban area as a whole. Models must also be capable of simulating the passage of flood flows through urban landscapes when drainage systems fail.

Responses employing Floodwater Storage ranked fourth, with real time control identified as a measure that could be made more effective through further work, particularly in existing urban areas, where storage opportunities are limited and the key to using them to reduce flood risk lies in making better use of storage through improved floodwater management during the event. This needs to be linked to spatial variability in rainfall patterns and real time storm prediction to better utilise dynamic operation and control of our urban drainage systems.

Asset management of existing urban watercourses and sewerage ranked fifth. In this response group there is a need to review the integrated operation of these systems recognising governance issues, whole-life costs and sustainability. The current complexity of responsibilities and ‘permissive’ approach to management of urban watercourses, for example, needs to be rethought to ensure that urban area flood ‘master planning’ becomes ubiquitous. Research should concentrate on solving problems that currently prevent the implementation of technically feasible responses: institutional and governance arrangements, investment strategies based on short-term economic perspectives and lack of structured approaches to asset serviceability and sediment and obstruction management. Such research will, in time, support reform of the complex institutional framework within which intra-flood risk is presently managed. What is also a required is recognition by stakeholders in urban areas of the continuing need to adapt to changing flood risk and a willingness to accept more responsibility at the local level.

Although groundwater management responses were found to be largely ineffective, they may well have a role in, for example, urban areas underlain by chalk. Research is needed, however, as there is little guidance available regarding sustainable approaches to selectively managing groundwater for flood risk reduction.

Responses to coastal erosion

In cases where erosion rather than flooding presents the primary hazard requiring a response, research priorities reflect uncertainties and limitations to knowledge that differ somewhat to those surrounding coastal flood management. Investigations performed during the responses phase have identified four priority topics, which are listed in Table D3 and are described below:

Priority 1: Modelling coastal geomorphology

As drivers of coastal erosion strengthen, both the extent and intensity of coastline retreat are predicted to increase. Responses may involve strengthening existing coastal defences, building new defences or

Table D3 **Priorities for further work to reduce uncertainty in responses to coastal erosion**		
Priority	**Topic**	**Disciplinary Area**
1	Modelling coastal geomorphology	Natural Environment, Engineering and Physical Sciences
2	Indirect approaches involving energy reduction and renewable energy extraction	Economic, Natural Environment Engineering and Physical Sciences
3	Managed realignment of coastal defences	Social, Economic, Natural Environment, Engineering and Physical Sciences
4	Sustainable beach recharge and recycling	Natural Environment, Engineering and Physical Sciences

employing managed retreat to allow the coastline to accommodate the forcing agents. Decision making on the appropriate response for a given location requires accurate prediction of the alternative patterns of morphological evolution under each of these management options, at both the local and coastal-cell scales. Major uncertainties exist due to the limitations of existing models to simulate cliff-beach interactions, cliff-infrastructure-beach interactions, and the wider consequences of erosion protection within the coastal cell and region, particularly through sediment starvation down drift.

- Research is urgently required to improve the capability of coastal morphological models to support decision making by providing accurate predictions of local morphological changes and broad-scale morphological responses to coastal engineering and management.

Priority 2: Indirect approaches involving energy reduction and renewable energy extraction

Increasingly, engineering approaches to preventing erosion favour reducing the intensity of the driving forces rather than hardening the shoreline to increase its erosion resistance. However, there is limited design guidance to support this approach, the design life of structures is unknown and experience gained to date shows that schemes involving off shore reefs and structures are liable to produce unexpected outcomes. Incorporation of renewable energy opportunities within coastal defence schemes is already beginning to be evaluated, but this is targeted at wholesale replacement rather than a partial contribution to the overall defence need. As the production and market for renewable energy matures there may be more scope for some partial combinations, where the energy device reduces the exposure of the coast but does not entirely eliminate the need for defences.

- Research is required to develop a much clearer understanding of the process-response mechanisms in eroding coastal systems benefiting from indirect protection, and the potential for energy to be extracted in multi-purpose schemes designed to manage coastal erosion and generate renewable energy.

Priority 3: Managed realignment of coastal defences

Examination of existing protection measures around the UK coastline revealed the great extent of defences that are necessary to protect infrastructure that runs along the coast, such as roads, railways, and pipelines. If infrastructure could be re-located to landward the need for substantial lengths of defence would be significantly reduced. However, relocation of infrastructure falls outside the scope of conventional coastal management assessments and the funding mechanisms to support it are difficult to envisage given that costs are likely to be high unless the particular infrastructure is due to be replaced anyway. Also, although infrastructure relocation and managed realignment are, in theory, desirable for sustainability and environmental reasons (the desire to retain a good range of inter-tidal habitats is likely to be a key driver) uncertainties concerning long-term morphological response and ecological impacts cloud the issue and make it difficult to account reliably for environmental benefits.

- Multi-disciplinary research combining economics, infrastructure management and coastal processes is essential to provide the methodological basis for assessment of the true costs and benefits of infrastructure relocation and managed realignment as a policy response to intensified coastal erosion.

Priority 4: Sustainable beach recharge and recycling

Beach recharge and recycling are likely to feature as a response to increased coastal erosion under all scenarios, but with important differences in the balance between the use of external sources versus recycling within natural sediment systems. Based on current experience, it will become more and more difficult to find suitable sources of sediment, especially for shingle beaches. This is inevitable due to depletion of finite Holocene sediment sources, but will be exacerbated in the more environmentally oriented scenarios due to concerns about the impacts of extraction from the seabed and offshore features and the need for repeated recharge. Widespread adoption of beach nourishment appears to be an attractive alternative to hard protection of eroding coasts, but to be sustainable it relies on careful sediment management.

- Further research into sediment sourcing and recycling is essential if the expansion of beach nourishment that is expected to occur in response to increased coastal erosion is to be achieved sustainably.

Strategic assessment of responses to future flood risk in the UK

Priority research areas are listed in Table D4 and are described below:

Table D4 **Priorities for further work in strategic assessment of responses to flood risk**

Priority	Topic	Disciplinary Area
1	Integrated approach to collation and dissemination of data	Social, Economic, Natural Environment, and Engineering Sciences
2	Real-time forecasting and flood emergency management	Social, Economic, Natural Environment, and Engineering Sciences
3	Decision support for long term planning in flood risk management	Humanities, Social and Engineering Sciences
4	Risk assessment for intra-urban flooding	Engineering and Physical Sciences
5	Post-event evaluation of the performance of flood defence measures	Social, Economic, Natural Environment, Engineering and Physical Sciences
6	Aggregation of diffuse and local responses in regional assessments	Natural Environment, Engineering and Physical Sciences
7	Evaluation of non-monetary, intangible items	Humanities, Social and Engineering Sciences
8	Contribution of river and coastal maintenance activities to reducing risk	Natural Environment, Engineering and Physical Sciences

Priority 1: Integrated approach to collation and dissemination of data

Improved technology for data collection, and better access to existing data, will characterise the future. However, to take up and capitalise on improved technological capabilities in practice, current work in enhancing flooding system databases must be maintained and, where possible, expanded. Further, data are only useful if they are accessible and work is required to widen stakeholder and public access to flooding databases.

- Work on improving existing databases of floodplain topography, river and coastal flood defences and people and assets at risk must continue. In addition, new research is required on how best to integrate different types of data from a variety of sources and make it readily available and accessible to all stakeholders, breaking through present sectoral boundaries.

Priority 2: Real-time forecasting and flood emergency management

To deliver many of the event management responses analysed in this Foresight project, flood forecasting needs to move beyond predicting source variables (rainfall intensities, river levels, storm surge heights etc) to forecasting the extent and severity of flooding and its consequences. This, necessarily, involves accounting for the performance of flood defences and drainage infrastructure. Given the uncertainties inherent to forecasting, what will be provided is a map of the probability of inundation during a given storm event. Conversion of improved predictions into loss reductions requires accurate real-time decision-making on, for example, deployment of temporary defences and evacuation of residents from areas where the probability of inundation is high.

- To be effective and sustainable, event management requires that measures are taken in time and that emergency resources are accurately guided and focused on vulnerable people in the areas most at risk as the event unfolds. A great deal of further research is required to deliver accurate, probabilistic flood forecasts that can be understood and acted upon by flood management organisations, the emergency services and local stakeholders.

Priority 3: Decision support for long-term planning in flood-risk management

Flood-defence infrastructure takes a considerable time to design and construct and flood defence policy and planning evolve slowly. Once in place, the operational life of a structural solution may be of the order of a 100 years, while policy-based solutions may take decades to become fully effective. Given the non-stationary condition of climate and socioeconomic flood risk drivers identified in the Impacts phase, it follows that taking a long term perspective on flood risk responses will not be possible using existing strategic assessments that provide snapshots of future conditions.

- Research is required to provide a range of science-based flood-risk assessment and management tools appropriate to the needs of different end users and stakeholders. For example, strategic risk-assessment methodologies, such as the RASP methodology used in this project, should be linked with simpler user interfaces, such as those developed through FloodRanger and the Modeling and Decision Support Framework, developed in the UK to support Catchment and Shoreline Management Plans. This could be a very powerful combination in enabling policy makers and managers alike to explore possible future scenarios and develop response plans that are robust to the dominant uncertainties within a given region.

Priority 4: Risk assessment for intra-urban flooding

Intra-urban flood risk derives from multiple sources; pluvial, fluvial, and coastal. The infrastructure used to manage floods is diverse, including above ground (linear defences, barriers) and underground (sewer pipe networks and controls) elements. Within this Foresight study the technique used for strategic assessment of future responses has limited consideration to fluvial and coastal flooding and above ground assets. No study of equivalent depth has been possible for pluvial floods and underground drainage systems in urban areas.

- An assessment framework capable of integrating the risks posed by multiple flood sources acting on sewer, flood and coastal defence assets above and below ground is required to provide the holistic view of flood risk that is essential to supporting a truly integrated approach to flood risk management under extreme conditions. Conceptual and practical research is urgently required to achieve this capability.

Priority 5: Post event evaluation of the performance of flood defence measures

Reviewing and learning from history provides a rich source of new knowledge and understanding. However, present approaches to flood forensics are weak and could be significantly improved.

- New integrated monitoring and analytical tools based largely on advances in remote sensing offer the opportunity to greatly expand data collection during flood events to support improved post-event assessments of asset performance. The possibility exists to share and exchange experience further a field with continental Europe and the Americas.

Priority 6: Aggregation of diffuse and local responses in regional assessments

The point impact of spatially diffuse responses such as changes in catchment land use through, for example, altered rural land management to retard flood flows, is difficult to resolve within the context of a strategic assessment without recourse to detailed hydrological modelling. Conversely, the sum effect of very local measures, for example householders floodproofing their properties, is difficult to characterise at the regional scale.

- Research is required to allow better resolution and characterisation in strategic assessments of unconventional responses to flood risk, in terms of their impacts in overall risk reduction.

Priority 7: Evaluation of non-monetary, intangible items

At present only those items that can be relatively easily valued in monetary terms are included within a strategic assessment. This clearly limits the ability of RASP-type methodologies to represent fully the social, welfare, health and environmental benefits of flood risk reductions that may be achieved through implementation of a particular portfolio of responses.

- New techniques should be developed to provide a more transparent approach to comparing tangible and intangible costs and benefits within a strategic assessment of risks, where it would not be possible to undertake a detailed site specific valuation.

Priority 8: Contribution of river and coastal maintenance activities to reducing risk

The Foresight study has found that new river and coastal defences are likely to figure prominently as responses to increased risk under all future scenarios. A significant proportion of current Flood and Coastal Defence investment is expended in maintaining the condition of existing FCD infrastructure. Any expansion of the extent or height of defences and the number and size of movable structures is bound to involve a higher maintenance bill.

- Detailed tools should be developed to elucidate the form of the relationship between expenditure on maintenance activities, the condition of defences, their performance under extreme loadings and the resulting impact on flood risk. This will involve a more detailed understanding of defence deterioration and failure mechanisms and the impact of alternative models for scheduling and prioritising maintenance.

Sustainability and governance of future flood-management responses

This Foresight project has brought into focus the extent to which sustainability is a process of learning and evolution that must be research-led. Our analysis of sustainability highlights the significance of cost-effectiveness, environmental quality and social justice dimensions of sustainability. Here we identify the highest priority research needs that derive from our analysis of sustainability and governance.

Priority research areas are listed in Table D5 and are described below:

Table D5 **Priorities for further work in sustainability and governance**

Priority	Topic	Disciplinary Area
1	Recognising whole-system costs and benefits	Social, Economic, Natural Environment, and Engineering Sciences
2	Delivering sustainability	Social, Economic, Natural Environment, and Engineering Sciences
3	Exploring institutional reform	Social Sciences and Humanities
4	Promoting adaptability	Social, Economic, Natural Environment, Engineering and Physical Sciences
4	Reducing uncertainty in the human and ecological consequences of realignment	Social, Economic, Natural Environment, Engineering and Physical Sciences

Priority 1: Recognising whole system costs and benefits

The costs and benefits of flood risk management responses to the human/environment system must be appraised more completely and realistically than has been possible in this Foresight project. Financial costing of assets at risk and the implementation of individual responses gives only a partial picture. The methodology used in this Foresight programme is novel in combining scenario analysis with quantitative assessments of flood risk and sustainability. The use of such mixed methodologies provides considerable insights but there is a need to optimise the approach.

- Research is required to develop approaches that account for the fact that the sustainability of responses hinges critically on the whole system costs and benefits of flood management. The strategic approach to risk assessment employed herein shows how this might be achieved, but the methodology requires further research to increase the scope of costs and benefits included and improve its ability to discern the whole system outcomes of specific measures or policies.

Priority 2: Delivering sustainability

The environmental benefits of responses involving rural-catchment storage, land use planning, coastal realignment and coastal morphological protection depend critically upon the way that they are implemented. Also, adverse impacts on social justice are associated with many otherwise attractive responses unless social priorities are well-managed. Sensitivity of sustainability parameters to the societal values and governance mechanisms mean that the same response may have social environmental costs in one future socioeconomic scenario, but not in another, reflecting differences in the basis and approach to its execution. In this context:

- There is an urgent need for research to develop a fuller understanding of how rural-catchment storage, land use management and planning, coastal realignment, and coastal morphological protection should be designed and managed to deliver, simultaneously, cost-effective flood risk reductions and environmental benefits.
- A key element in delivering social justice is to explore more fully the factors that determine the perceptions of flood risk and how to manage the problem of risk awareness in societies where there are often conflicting messages and where flood risk is changing rapidly.

Priority 3: Exploring institutional reform

The priority areas for further research listed in the sections of this Appendix dealing with responses at the catchment/coastal and urban scales stress the urgent need for improved understanding of the planning/management dimension of flood management in both rural and urban contexts. Foresight analysis highlights that the complex institutional framework within which flood risk is presently governed currently prevents the implementation of responses that would be technically feasible, effective and sustainable. It is also identified that further progress requires that stakeholders recognise the need to adapt to changing flood risk and demonstrate their willingness to accept more responsibility for risk management at the local level. However, it is clear that the institutional regimes and governance structures necessary to deliver strategic and local flood risk management effectively and sustainably cannot currently be defined and described with confidence.

- Further research projects and field investigations in the social and behavioural sciences are required to identify how institutional reform could unlock the potential for implementation of new and innovative techniques for flood risk management. The research must be performed within a participatory framework and within the context of a sustainability framework.

Priority 4: Promoting Adaptability

Adaptability emerged as a key attribute of responses in that it allows policymakers and flood defence designers to manage the wide uncertainty concerning future climate, societal and economic changes. However, analysis of response themes and groups suggests that adaptability may be undervalued in current approaches to the evaluation of alternative flood management strategies. Further, the Foresight analysis reveals that adaptability is maximised when flood management employs an integrated portfolio of responses, rather than relying on just one or two measures, interventions or policies.

- There is a need to research how to deliver a flood risk management portfolio of responses in a flexible manner that is responsive to changing challenges and conditions on both a temporal and spatial scale.

Priority 5: Reducing uncertainty in the human and ecological consequences of realignment

The consequences of managed realignment of coastal and river defences for people and ecosystems are particularly unpredictable. This is unfortunate as it makes it difficult to identify benefits and reduces the credibility of this approach as a win-win solution to a flooding problem. Full stakeholder participation and on-going environmental monitoring provide the best scope for evaluating realignment alternatives in the context of environment/human systems.

- Further research is required to identify why different realignment sites develop in different ways and develop the capacity to predict with confidence the outcomes of managed realignment for the communities and ecosystems affected.

The Science Package

Introduction

From its inception, the Foresight project recognised the overarching need to think radically in exploring the full range of potential responses in managing future flood risk and coastal erosion. This has been achieved not only in a practical way, by considering a wide spectrum of relevant sciences and technologies, but also philosophically, by allowing the project experts the freedom to investigate their own and others' unconventional and 'out of the box' ideas. In this way, the search for new and innovative solutions has been informed, but unconstrained by, current expertise and methods.

The project's 30-100 year timeframe demands that, in the search for solutions, we look at both tried and tested and hitherto unconsidered fields of science and technology. A cross-disciplinary approach is axiomatic of OST's Foresight programme and, therefore, also a key FCD project objective.

These objectives were promoted through providing a clear steer and support to the contracted work package managers in leading their expert teams; in particular, experts were encouraged to seek contributions and ideas from a wide range of stakeholders in promoting the identification of radical solutions (using public consultation exercises, existing networks, workshops, brainstorming sessions and the like). In addition, the exploration of cross-disciplinary approaches was addressed in the project's 'Science Package'.

The outcomes of the contracted experts have already been covered here in the preceding sections of this appendix and the 'emerging issues' commentaries in the response descriptions (Appendix A). Here we present summary overviews of stakeholder suggestions on radical thinking and the recommendations of a workshop on the rôle of sensor networks and remote sensing in managing flood risk reduction.

Radical thinking

As part of the wide consultation undertaken during the Foresight project, we invited stakeholders to submit radical ideas for responses to increased risks of flood and coastal erosion. The aim was to avoid restricting consideration of responses to extrapolation of existing ideas and approaches. In all, 38 ideas were forth coming and these are grouped by response theme and described briefly in Table D6. The status of each idea, in terms of the degree to which it was proven or speculative, was assessed and is indicated in column 3 of Table D6 as:

Category P: Ideas in current use in the UK to greater or lesser degrees

Category 1: Ideas currently used abroad but not yet adopted in the UK

Category 2: Ideas where the science is proven but the concept has not been tested in the field

Category 3: Ideas where science breakthrough would be needed before it could be used

Category 4: Far off ideas

Most of the radical ideas recorded in Table D6 were considered during the Foresight project within the contexts of the response groups indicated, but all are listed here to indicate the breadth of possible ways forward in responding to future flood risks and recognise the contributions made by interested stakeholders.

Table D6 lists radical ideas that have been suggested by a wide range of stakeholders. These ideas, and the comments on them by project experts, are provided to stimulate discussion. They do not represent the views or recommendations of either the OST or Government.

Table D6 **Radical ideas for responses to increased risks of flooding and coastal erosion**

No.	Radical Idea	State	Originator and affiliation	Response group(s) in Appendix A/B	Comments
			Theme 1: Managing the Rural Landscape		
1	Afforestation	P	George Lees: Scottish Natural Heritage	A1-3	Increased planting of native trees in headwaters to increase infiltration, reduce peak flows, improve water quality (see also 2). This suggestion is an extension of responses already covered in the relevant groups.
2	River flood retardation in woodland	1	Paul Carling: Univ. Southampton	A2-3, A4, A19, B2	Purchase or lease recreational or economic woodlands that could be purposefully or naturally flooded. Flow through woodland spreads and retards the flow rate, reducing downstream flood levels. This suggestion is an extension of measures covered in the existing response themes.
3	Catchment control	3		A1-3	Recognising scale effects, employ set-aside, ESA's and other incentives to persuade land owners to manage land in ways that reduce flood runoff. This idea is covered in existing response groups.
			Theme 2: Managing the Urban fabric		
4	Urban tarmac removal	P	George Lees: Scottish Natural Heritage	A5, B3-4	Where feasible, replace impermeable surfaces by permeable materials in urban areas to increase infiltration (see also 7). This idea is covered in the Response Group A5 – Urban Infiltration.
5	Measures to reduce plastic-bag use	1		A6, B6	Measures to reduce plastic bag use and consequent blockage of trash screens and culverts, thus contributing to reduced maintenance and increased conveyance. A complete ban on plastic bags has been very successful in reducing drain blockage in Dhaka, Bangladesh.
6	Remove culverts	P		A6, B6	'Daylighting' through removing culverts, thus contributing to increased conveyance. This suggestion is already covered in relevant response groups.
7	Buffer floods in urban areas	P	David Lawson: STRI Ltd.	A4-6, B2	Use 'soft' urban landscapes to increase infiltration, reduce runoff and manage conveyance (see also 4). The measures proposed here are already covered in the relevant response themes.

Table D6 **Radical ideas for responses to increased risks of flooding and coastal erosion** *(continued)*

No.	Radical Idea	State	Originator and affiliation	Response group(s) in Appendix A/B	Comments
8	Flood storage in multi-use areas	P	Paul Carling: Univ. Southampton	A2, A4, B5	Create/employ recreational areas as temporary flood reservoirs with attendant social/environmental benefits (see also 2, 4 and 7). Already in use. Covered in the relevant Response Groups.
9	River flood routing in urban areas	1		A4, A6, B2, B5-6	Use of roadways to increase conveyance and parks to buffer flood flows. These ideas are covered in the relevant Response Groups.
			Theme 3: Managing Flood Events		
10	Skills for major emergencies	P	Alastair Robertson: 5S Consulting	A9, A10, A16-17	Auditing of emergency response skills to improve responses during flood emergencies. The ideas proposed here are covered in the themes Managing Flood Events and Managing Flood Losses.
11	Improving flood level predictions	2	George Heritage: Univ. Salford	A7, A8	Use oblique LiDAR to increase accuracy of floodplain surveys, to support improved flood propagation modelling and prediction. Improved take up and application of remotely-sensed data is covered as part of the Science Package reported here.
			Theme 4: Managing Flood Losses		
12	Stakeholder participation in managing risk	P	Emma Tompkins: Tyndall Centre	A10, A12, A14, A21, A23, B2	Decisions on flood management should be based on flood risk assessments that are zoned, public and available to insurers and house buyers. Decision-making should involve a process of stakeholder consultation and participation (also related to 14 and 15). This is essentially current practice.
13	Non-structural solutions	P	David Chrichton: Benfield Hazard Research Centre – UCL, FHRC – Univ. Middlesex, and Univ. Dundee	A12-15, B1-2	Reduce consequences of flooding through stringent land use management and planning rules to avoid building in flood prone areas wherever possible, plus advanced floodproofing to make buildings at risk more flood resilient – as in Australia (see also 14, 16, 17, 20, 26). Essentially, strong versions of responses already covered in relevant themes of Catchment, Coastal and Intra-urban responses.
14	Zoning of river and coastal floodplains	P	George Lees: Scottish Natural Heritage	A12, A14, A23, A26, Coastal Erosion	Flood zoning to prevent inappropriate future development. Allow river and coastal floodplains to fulfil their natural functions. (see also 13, 15, 16, 17, 20, 26, 27). This is essentially current practice.

Table D6 **Radical ideas for responses to increased risks of flooding and coastal erosion** *(continued)*					
No.	**Radical Idea**	**State**	**Originator and affiliation**	**Response group(s) in Appendix A/B**	**Comments**
15	'No go areas'	P	Richard Holmes: British Geological Survey	A14, A 23	Designate areas prone to flooding and/or coastal erosion as 'no go areas'. Withdraw from current developments and allow no new ones in these areas. This approach represents an extension of responses envisaged under the Local Stewardship scenario (see also 13, 26, 27, 16, 17).
16	Relocation of communities	1	Paul Carling: Univ. Southampton	A12, A14	Relocate small communities where it is cost effective to move them rather than provide engineering defences. This has been employed in other countries, but is seldom feasible economically. It represents a strong form of reducing exposure through land management and is covered by that response group.
17	Redesign small communities	1		A13, A15, B1	Change use of ground floor in flood prone buildings, flood proof to reduce damage (see also 13). These ideas are covered in the relevant response groups.
18	Designing out flood vulnerability in housing	1	Jason Foley: Eades Hotwani Partnership	A13, A15, B1	Adopt a 'Protection by design' approach to housing in flood prone areas through developing and adopting new architectural and landscaping design principles. These ideas are covered in the relevant response themes.
19	Raised houses	1	David Prandle: Institute of Oceanographic Sciences	A15	Flood resilience of new buildings in flood prone areas could be increased by raising their ground floors 1m above ambient level, as done in Canada (see also ideas 13 and 17). This type of approach is already covered in Response Group A15.
20	Mobility of new build	3	George Lees: Scottish Natural Heritage	A15	Construct new buildings near the coast or adjacent to dynamic rivers with the capacity to be dragged or rolled landward in the event of future erosion. This essentially a radical extension to Response A15.
			Theme 5a. River Engineering		
21	River flood diversion	P	Paul Carling: Univ. Southampton	A20	Use inter-basin transfers to divert river floodwaters through tunnels to neighbouring river systems. This idea is already covered in Response Group A20.

Table D6 **Radical ideas for responses to increased risks of flooding and coastal erosion** *(continued)*

No.	Radical Idea	State	Originator and affiliation	Response group(s) in Appendix A/B	Comments
22	The Floodsucker	2	Stephen Salter: Univ. Edinburgh	A18	The Floodsucker is a straight duct containing a large, vertical-axis variable-pitch Voith-Schneider rotor which can move 20 to 30 cubic metres of water per second, against a head of one metre and can also give the system self-mobility. Floodsuckers could be deployed to decrease flood levels in rivers in urban areas by pumping to water further downstream or out to sea.
23	The C dam	2	Stephen Salter: Univ. Edinburgh	A4, A19	A membrane dam, similar to those used in some forms of temporary and demountable defences, used to store floodwater, up to a depth of 7 metres. See also 8 and 9.
24	Replacing bridges with tunnels	2	George Lees: Scottish Natural Heritage	A3, A6, A18, B6	Replace bridges, causeways and other air crossings that act as 'choke points' in rural and urban conveyance systems with tunnels. This would be expensive, with major implications for national heritage.
25	Dredging reservoirs	3		A19, B5	Dredge sediment from reservoirs and ponds to increase flood storage capacity. Spoil disposal a problem for contaminated sediment. Improvement only achieved if 'live storage' is recovered.
			Theme 5b. Coastal Engineering		
26	Defence realignment	P	George Lees: Scottish Natural Heritage	A21, A23-24, A26, Coastal Erosion	Realignment or removal of linear defences and restoration of natural functions of formerly protected areas (see also 13, 15, 16, 17, 20). Essentially, strong version of realignment/abandonment responses.
27	Planned settlement retreat	P	Roger Few: Univ. East Anglia	A12, A14, A23, A26, Coastal Erosion	Broad scale, long term integration of planning and Shoreline Management Plans to support phased withdrawal of settlements from the coast in areas prone to flooding or erosion. Compensatory systems formulated to avoid blight and other social costs without imposing a high burden of public expenditure. Essentially, an extension of managed realignment covered in coastal response themes to 'coastal rollback'.
28	Chemical treatment of soft coastlines	1	Andrew Gibson: British Geological Survey	A21, A2, Coastal Erosion	Harden soft cliffs against erosion. Potential beneficial effects on coastal erosion and land loss locally, less impact on flood defence. Effectiveness is unproven, but might be worth initial experiments to quantify increased resistance to direct wave erosion, groundwater softening, and land slides.

Table D6 **Radical ideas for responses to increased risks of flooding and coastal erosion** *(continued)*

No.	Radical Idea	State	Originator and affiliation	Response group(s) in Appendix A/B	Comments
29	Appealing erosion	2	John Rees: British Geological Survey	A23, A25, A26, Coastal Erosion	Develop eroding coasts as landscape attractions and educational/research resources. This is a strong form of morphological protection through allowed erosion that could, in the long term, reduce nearshore energy and the deleterious impacts of coastal erosion, and contribute to flood defence.
30	Flood embankment fragility	2	Mark Dyer: Univ. Durham	A21, A22	Develop a better understanding of the role of fissures in promoting breaching of flood defences to support improved condition and risk assessments. This topic is already given a high priority for further work in Appendix D of Volume I, as well here (Priority 7 in Table D1 and Priority 8 under Strategic Assessment).
31	Reversing subsidence	3	Chris Rochelle: British Geological Survey	A18, A25	Inject material (solid + water) to increase local land levels in subsiding, flood prone areas. In fluvial and marine contexts this might have local effects on probability of flooding. At the coast, it could also refocus wave energy, reducing net drift and introducing crenulation into the shoreline (see also 34).
32	Restoration of a tidal haven	2	Colin Taylor: British Energy	A23, A26, Coastal erosion	At a site including Minsmere, is an old tidal haven. It is fronted by a single barrier of shingle and sand dunes and long term studies suggest there will be an increasing risk of a breach occurring there. If a breach were to be permitted through active management a tidal haven could become re-established, improving long term protection and generating environmental benefits. This is a specific example of managed realignment and morphological protection combining measures proposed in Response Groups A23 and A26.
33	Protection of critical coastal infrastructure	3		A23, A26, Coastal Erosion	Currently an SoP of 1 in 10,000 is set for certain critical infrastructure along the existing operational flood defence line, peripheral to the site. It is proposed that at sites fronted by a modified shingle (soft defence) shore the critical infrastructure itself be engineered to provide its own flood defence, with the residual footings of operational buildings to seaward providing a degree of erosional defence. The existing shoreline could then be allowed to revert to a natural form saving money and allowing the coasts natural functions to recover. This is a special case of coastal realignment, specific to certain types of critical infrastructure. It could have considerable benefits.

Table D6 **Radical ideas for responses to increased risks of flooding and coastal erosion** *(continued)*

No.	Radical Idea	State	Originator and affiliation	Response group(s) in Appendix A/B	Comments
34	Reduce wave energy or raise subsiding areas	3	John Huthnance: Natural Environment Research Council	A25, A26, Coastal Erosion	Use cold water reefs or power extractors to reduce wave energy reaching shoreline, or use "oil on troubled waters" or coverings on beaches (what happens if snow is blown over the beach?) to reduce wave erosion effectiveness. These ideas are covered in Response Groups A24 and A26. Some parts of the coastline are sinking because of groundwater extraction and could be raised through groundwater recharge using seawater (see also 31). This idea could have implications for groundwater quality.
35	Used-tyre reef to reduce wave energy	3	Stephen Salter: Univ. Edinburgh	A25, A26, Coastal Erosion	This proposal is a mix of conventional wave reduction by building artificial reefs but novel in that scrap tyres would be used to form those reefs. There could be environmental objections and the feasibility/durability would depend on local sediment conditions.
Not covered in any Foresight Response Theme					
36	Pre-emptive cloud seeding	3	Stephen Salter: Univ. Edinburgh	none	Pre-emptive cloud seeding of dangerous weather systems in mid-Atlantic to reduce the quantity of water that is left when the weather system reaches the UK. This is a response that treats the source of catchment and, to a lesser extent, intra-urban flooding that is not covered by any of the Foresight responses. The effectiveness of seeding clouds in the humid mid-latitudes is, however, unknown.
37	Reduce sea level rise	4		none	The expected rise in sea level is about 1 m. The area of the oceans is about 3.7 x 10^{14} m^2, while the area of land with lower than desirable water tables is about one seventh of this. If the void ratio of the rocks below the deserts is 0.2, pumping sea water into the ground beneath deserts to cause a rise in the water tables of 35 metres would result in a fall of ocean levels by 1 m. Alternatively, wind-powered turbines could be used to enhance evaporation from the oceans. Either approach could theoretically negate the expected sea level rise. These ideas are not covered by any of the Foresight responses.
38	Increase cloud albedo	4		none	Global warming caused by greenhouse gases, which retain solar heat, could be negated if cloud albedo were increased to reflect more solar radiation back into space. In theory this could be achieved by adding relatively modest amounts of water to clouds in droplets. It is unclear whether this response would be employed locally or regionally.

Cross-connecting sciences with flood-risk management: an example

As part of the science work-package, a workshop was held to consider the possible use of remote sensing and sensor networks for coastal defence, with a particular emphasis on defence deterioration, bathymetry and early warning systems. This was to explore the possibility of connecting flood managers with developments in other areas of science. The discussion was wide-ranging and multidisciplinary and raised a number of possibilities for future action, which are summarised below.

The key new enabling technology identified by the workshop participants was ubiquitous smart sensing, using wireless sensor networks, and the workshop report provides a brief review of the state of the art in sensor networking, identifies the key UK and European research groups that are actively exploring the application of this technology to external environments, and lists their main sources of funding. The report concludes that small-scale, trial deployments are possible now, but nation wide deployment with desirable capability at reasonable cost could be only 10-15 years away, but more realistically might take 15-30 years. The key research issues relate to:

- Ease of use and management.
- Data fusion and aggregation.
- Public acceptance.

Summary

The main outcome of the workshop was recognition that new, low cost, minimal infrastructure approaches, of the kind being investigated by sensor networks research, had exciting future potential for flood-risk management. In particular suggestions for intelligent drain covers, dense fibre-optic sensing and dense GPS were widely regarded as promising. It was also recognised that, in order to succeed, initiatives based on low cost (low accuracy) widely distributed sensors would require:

- Sensors to have enough intelligence to configure and maintain themselves.
- Integration with existing measurement approaches and existing data, as well as with other emerging measurement possibilities (not an exclusive solution).
- Significant levels of public support and understanding to reduce vandalism.

- Encouraging councils to facilitate public contributions to observations (and ownership) could be a way forward.

In the light of this outcome further work was performed to define the current state of sensor networking research and development in the UK.

Research issues and timeline

The advice of the consultation group on emerging technologies for coastal defence, focused strongly on the opportunities presented by wireless sensor networks ('smart dust') for monitoring coastal defences and the processes that act on them. In particular the simultaneous emergence of cheap microcontrollers, cheap wireless communication and intelligent autonomous software could enable the emergence of novel products that could be deployed at high density without incurring excessive capital cost and that would survive for long periods of time without incurring significant maintenance costs.

At present, although the component technologies are advancing rapidly and basic research on wireless sensor networks for environmental monitoring has commenced, the credible industry players and skills that would be needed to collaborate to produce complete system scale solutions are highly fragmented. Due to the diverse nature of skills required, this barrier is unlikely to be overcome easily. Lack of visibility of the scale of the marketing opportunity for reuse of the coastal monitoring solutions for remote telemetry in the water, power, oil, telecommunications, agriculture and insurance business sectors does not help.

An approach to break down the barriers identified above would add value as it would facilitate the emergence of a new and lucrative UK-based industry that could provide solutions world wide. Partners to achieve this would include major industry players, the wide range of existing SMEs in the area, director's of emerging start-ups, professional consultants, potential customers (both commercial and governmental), and academic researchers from computing, electronics, environmental informatics environmental science and other relevant research areas.

In general, it was felt that aspects of this emerging technology could be used to solve local problems immediately, and that such localised application could be widespread within 5 years. However, national scale deployment at reasonable cost would take 15-30 years. This assessment appears to be pragmatic given the scale and type of existing experiments.

It was recognised (and the survey confirms) that there are a number of issues that, if addressed, could facilitate and speed-up the application of these technologies:

- An important structural issue in this area is linking the largely academic-led existing research initiatives with an appropriate and complete set of industry partners, motivated to supply and integrate the products required by a national-level infrastructure. It is worth noting that the required skill base is broader than that for pervasive computing due to the specialist hydrology and civil engineering skills involved.
- The research would also benefit from stronger links with the user community to ensure developments and prioritisation is appropriate to end user needs. Progress in this area has started but more would be useful.
- There are a range of technical issues at the individual sensor package level that so far have not been fully addressed but which would need to be solved. These include manageability, usability, automation, power sources, data handling and analysis.
- There are many technical issues at the system integration level, including data fusion, modelling of complex systems using dense input data, effective dissemination to users, standardisation and re-use of components. These issues cannot be well addressed by traditional research and development structures and will require an integrated approach to facilitate progress.

Conclusions

Dense networks of low cost sensors could play a key role in improving understanding of bathymetry and physical processes affecting it. They could also make possible advances in the understanding of other aspects of hydrology and facilitate effective flood warning. Assessment of degradation of existing defence works using this type of technique would require invasive engineering but, over time, would be feasible and useful. To maximise the benefits of deployment of dense sensing networks they would need to be integrated with other techniques and existing data. The sensors would also support re-use for applications other than coastal defence.

The technology is currently far from mature, nevertheless the pragmatic nature of initial developments means that rapid localised deployment and iterative development are possible immediately. Full scale national networks would probably take 15-30 years. The UK currently leads Europe in this area, and there is a significant opportunity for UK plc in facilitating and supporting the emergence of a viable integrated industry that can provide solutions across Europe and elsewhere.