Appendix B

Driver descriptions: intra-urban

Chapter 3 identified the 15 most important drivers of future flood risk at the intra-urban level. Some of these are the same as the catchment scale drivers (described in Appendix A) and operate in similar ways – they are not discussed further in this Appendix. All of the other intra-urban drivers are now described in detail. Further descriptions of the drivers (in still more detail) may also be found in the supporting technical documentation of the Foresight Flood and Coastal Defence project.

The intra-urban drivers described in this Appendix are set out in Table B1 which classifies them according to their place in the source-pathway-receptor model described in Chapter 1. Some of these are similar to catchment scale drivers but operate differently in the intra-urban environment. Others are unique to the intra-urban flooding processes.

The following information is provided for each of the drivers:

- A description of the driver and how it affects intra-urban flood risk.
- Its interaction with other drivers.
- Its influence on flood risk.
- Uncertainty associated with the driver.
- Case examples where appropriate. Further case examples are provided in Chapter 5.

Table B1 **Drivers of future intra-urban flood risk**

Driver group	Driver	Type
Climate change	B1: Precipitation	Source
Runoff	B2: Urbanisation	Pathway
	B3: Management of Peri-Urban Rural Land	Pathway
Urban conveyance systems and processes	B4: Environmental Regulation	Pathway
	B5: Urban Watercourse Conveyance, Blockage and Sedimentation	Pathway
	B6: Sewer Conveyance, Blockage and Sedimentation	Pathway
	B7: Impact of External Flooding	Pathway
	B8: Intra-Urban Asset Deterioration	Pathway

Driver

B1: Precipitation

Driver group: Climate change
Type: Source

Definition and operation

The Precipitation driver contributes to flood risk within the urban area through the hydrological distribution of precipitation in space and time.

The rainfall depth of a particular storm event is characterised by the rainfall intensity and the duration of the event. Each event occurs at a known frequency (return period). For the urban area it is possible to design or simulate the performance of the drainage system using design events, either as uniform-intensity rainfall, a storm profile (rainfall hyetograph) or a time series of events, typically an annual or 10-year series, or measured storm events.

Urban drainage systems are usually designed for storms of relatively short duration, typically a few hours of intense rainfall. Mathematical modelling of the performance of existing urban drainage systems during storms generally simulates the system's performance at short time intervals, typically only seconds in duration. Hence in an assessment of future flood risk for the different climatic scenarios it is important to have information on how rainfall within the urban area will change over short durations. We can now derive rainfall information from:

- the Flood Estimation Handbook for existing rainfall, with 10-, 30- and 100-year return periods.
- the Medium High scenarios of the UK Climate Impacts Programme (UKCIP98).
- UKCIP02.

The latest scenarios from UKCIP suggest that the UK's annual rainfall will decrease slightly, with a reduction of between 0 and 15% by the end of the century, depending on location and the assumed scenario of future greenhouse gas emission (Hulme et 2002). UKCIP02 suggests that winters will become wetter and summers drier, with the greatest accentuation in the seasonal cycle in the south and east.

However, for rainfall in urban areas there is significant uncertainty in the predictions of UKCIP98. Morover, most recent forecasts from UKCIP02 were different to the UKCIP98 predictions, with greater seasonal variability. In addition, a number of other urban-specific aspects are inadequately accounted for in the prediction, of rainfall such as local heat-island effects (see Chapter 5). Hence, this study considers the range of uplifts identified by both the UKCIP98 and UKCIP02 studies. In respect of future predictions, we have broken down these uplifts in rainfall into storms that are appropriate for the urban area.

The way in which rainfall is transformed into runoff is through the science of rainfall-runoff modelling. Within the urban area, the runoff is not a linear to response to precipitation: a number of surface processes occur that result in a loss, either immediate or continuous, that reduces the amount of rainfall that is available to runoff. Subsequently, the overland flow processes that occur are also non-linear.

It is by modelling that we try to understand how changes in all aspects of precipitation – amount, intensity, duration, location and clustering – will affect the flooding system. Obviously, increases in rainfall at all scales will increase the risk of flooding to a greater or lesser extent. However, decreases in average rainfall could see an increase flood risk if the mean decrease is coupled to an increase in the intensity or clustering of events. Both these scenarios are suggested within UKCIP02.

Individual urban areas have many different catchment characteristics. Hence their runoff response to precipitation events is different. For example, small and steep catchments are sensitive to changes in short-duration rainfall, whereas the runoff from larger catchments with a larger peri-urban area may be greatest for events of longer duration.

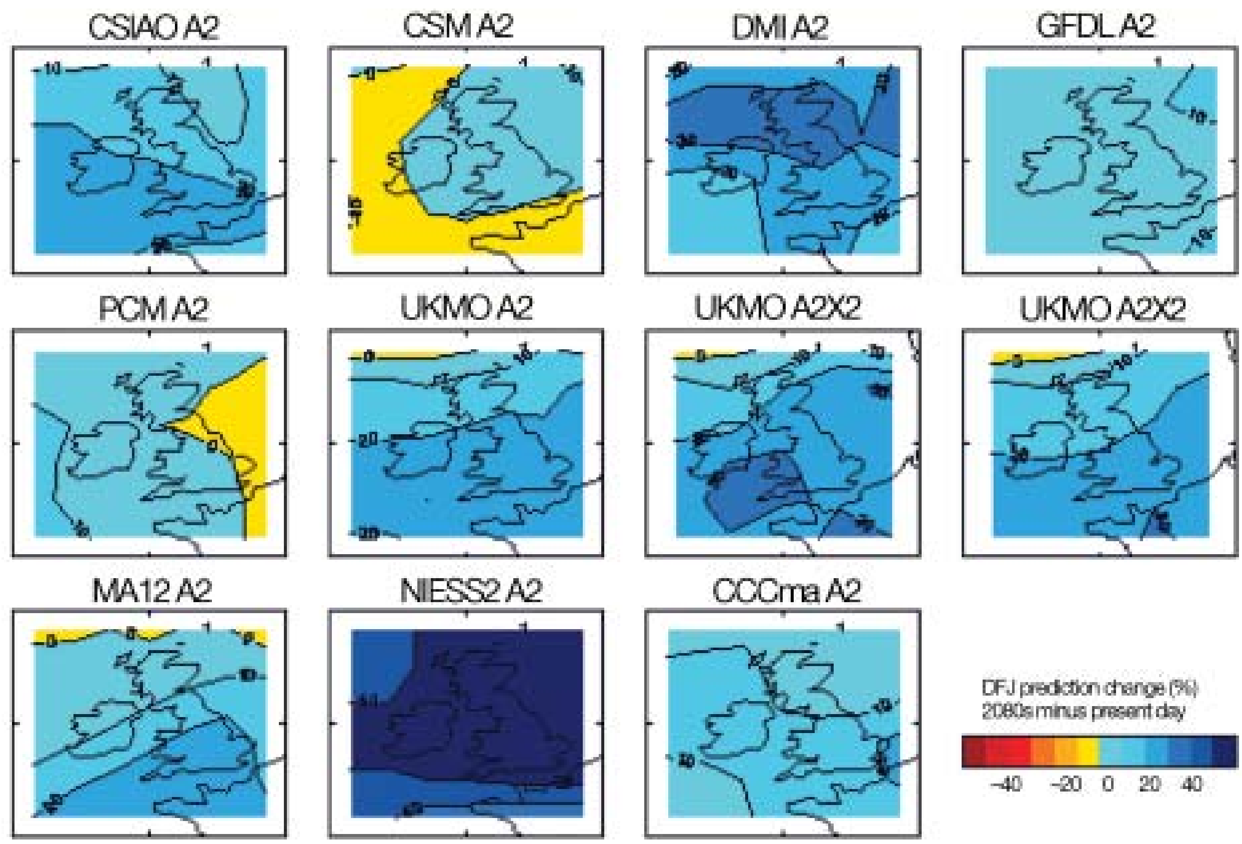
Interactions with other drivers

Precipitation is the key driver within the urban area and hence interacts with all drivers of runoff and conveyance.

Effects on flood risk

Assessing the impact of climate change on flooding within the urban area presents many challenges. These are most often addressed through hydrological modelling, generally using a continuous-flow simulation approach. Climatic input data series (principally precipitation and urban catchment wetness) are used to generate overland flow within the urban area which subsequently interacts with the below-ground drainage systems, including any infiltration from groundwater. Such interactive models are currently under development.

Figure B1 **Change in winter precipitation for the UK as simulated by nine global climate models (adapted from Hulme *et al.* 2002 and IPCC 2001a)**



Uncertainty

It is difficult to predict changes in rainfall over the next 100 years that are relevant to intra-urban flooding. Scenarios derived from different global climate models produce estimates of change in precipitation that are not only very different in size, but also in scale and direction (see Figure B1, Hulme *et al*. 2002; IPCC 2001a). These differences are further compounded since intra-urban flooding processes are subject to storms with even smaller spatial scales and with shorter time intervals and shorter durations. In addition, there are degrees of uncertainty depending on the aspect of the rainfall regime that is being investigated.

Driver

B2: Urbanisation

Driver group:	Runoff
Type:	Pathway

Definition and operation

Urbanisation is the change in land-use under which greenfield sites and pervious surfaces are covered with less pervious materials, including buildings and infrastructure, and associated new water conveyance systems.

Urbanisation is any increase in the extent of new urbanisation of the peri-urban area that drains, via a new drainage system, to the existing drainage system of an intra-urban area. It also includes any increase in the impervious area that drains to the existing drainage system within an existing intra-urban catchment. This might include, for example, the construction of patios, extensions to property and so on. All of these can increase the volume of storm run-off, reduce travel times, increase flood peaks, reduce groundwater recharge and reduce low flows. Secondary effects, and their mitigation, depend on the design and performance of the drainage system, although capacity to accommodate extreme events is limited.

The effect of urbanisation is to increase flood risk.

Interactions with other drivers

There are strong links between precipitation and the driver Infrastructure Impacts, associated with the management of peri-urban land and rural land as a pathway and a receptor. There is also high interaction with the socioeconomic driver group Social Impacts and the Human Behaviour driver group, including the driver Public Attitudes and Expectations, especially in respect of the acceptability of regulation and flood control solutions.

Effects on flood risk

Assessing the impact of urbanisation on flooding presents many challenges. These are most often addressed through hydrological modelling, generally using a continuous-flow simulation approach to assess the impact of changes in urbanisation. Flows and flood volumes are predicted but modelling approaches are uncertain.

Uncertainty

At the local scale, the interaction between the new and existing drainage systems is uncertain, as is the estimation of surface flooding due to the extent of the urbanisation.

Driver

B3: Management of Peri-Urban Rural Land

Driver group: Runoff
Type: Pathway

Definition and operation

Changes in the management of land adjacent to the urban area that influence runoff into the urban area, for example, muddy floods.

There is a growing perception that changes in land use and land management may have a significant impact on flood risk. The link between agricultural practice and the needs of the partially urbanised area has seen changes in land-cultivation practice, the increasing use of heavy machinery and an increase in the intensity of animal stock. Associated with all of these is the need for the expansion of farm buildings. These changes, together with the need for the additional urbanisation of the peri-urban area, has seen significant changes in the volumes of runoff that enter the urban area from the peri-urban area, including the effects of reduced infiltration and increased overland flow.

The runoff is a function of the slope of the catchment, for example, steep catchments create flood effects that are often more devastating due to the high velocity of the flow when compared to flooding by ponding. In some cases this runoff is accompanied by extensive soil erosion, and leads to the potential for muddy floods to enter the urban area. There is therefore the potential to effect changes in land-management policy within the peri-urban area to mitigate the flood risk within the urban area.

Interactions with other drivers

There is a strong interaction with the Precipitation, which determines the volume, peak flow and duration of runoff from the peri-urban area.

There is a strong interaction with Land Management as to how this runoff is managed due to changes in land use and with Public Attitudes and Expectations.

Case examples

There have been no specific studies to assess the impact of peri-urban land use. There are proposals to address this as part of the current EPSRC/Industry funded programme Adapting Urban Drainage for Climate Change, (AUDACIOUS), and the flood risk management research consortium (FRMRC) set up by the EPSRC, EA, Defra, NERC, Scottish Executive and UKWIR.

Effects on flood risk

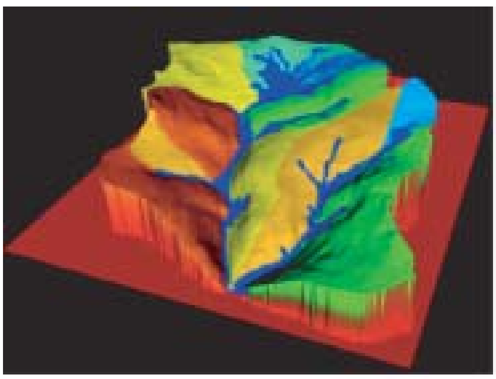
Assessing the impact of the management of land within the peri-urban area is attempted by hydrological modelling usually within a Geographic Information System (GIS) framework (see Figure B2). Flows and flood volumes are predicted but modelling approaches are uncertain, particularly in respect of flow paths and the impact of changes in land use.

Uncertainty

There is considerable uncertainty in the mathematical modelling of changes in the volume, peak and duration of runoff that result from changes in land-use management and the flow paths that floodwater takes as it travels overland, within these different land-use systems, from the peri-urban area into the urban area. Similarly, there is uncertainty in the extent of inundation due to the interaction of peri-urban flows and underground drainage.

There are also major uncertainties concerning the complexity of effects on a local scale due to changing land management, but these are a function of the different climatic and economic scenarios. To date, there has been little research to assess such effects.

Figure B2 **Runoff from the surrounding peri-urban area can deliver floodwater into urban regions**



Driver

B4: Environmental Regulation

Driver group: Urban conveyance systems and processes
Type: Pathway

Definition and operation

The management of the green areas within the urban landscape, including flora and fauna.

In future, decision-making to increase environment protection – watercourse pollution, biodiversity and habitat – will prescribe flood-management policy. Of particular relevance to such regulation and policy is the UK's interpretation and adoption of the EU Water Framework Directive and the Habitats Directive.

Enhanced day-lighting of urban streams and increased use of available green space to provide additional flood storage are both envisaged. Environmental improvements will be addressed by more detailed consideration of the discharges to urban watercourses from highways, surface-water drainage and combined sewer systems with improved understanding of existing system performance and the introduction of new pollution-prevention technology. The impact of increased volumes of raw sewage may influence receiving water quality and habitats whilst in contrast, changes in regulation and infrastructure may negate these.

Urban sediments and the consequent morphological change to the urban watercourse will result in changes to the flow paths and characteristics of the flow – depth, cross-sectional shape, velocity and so on – thereby affecting habitats and the propensity for changes in flora and fauna. The selection of the correct maintenance strategy for the urban watercourse corridor is therefore a key management driver.

In addition, we need to consider the changes in the environment within the urban area that is local to property. Here changes relate to the responsibility of the individual property owner, the local authority and the providers of water services. The management strategy within this local area will see the introduction of new technology to reduce flood risk and its impact on the local environment.

Interactions with other drivers

There will be high interaction with Precipitation, which determines the volume and magnitude of runoff into the urban watercourse and the consequent impact on the environment of the urban watercourse.

There will be strong interaction with Sewer Conveyance, Blockage and Sedimentation and the performance of the sewer system, particularly in areas local to property.

There will also be strong interaction with Stakeholder Behaviour in respect of policy, regulation and management strategy and with the Social Impacts associated with the improved aesthetic and pollution quality of the urban watercourse corridor and the local urban community.

Effects on flood risk

Assessing the impact on the environment due to changes in management strategies and regulation within the urban area is a considerable challenge and current methodologies to address such impacts are in need of development. Examples of the impact on the environment within the urban area are shown in Figure B3.

Uncertainty

The shape of future legislation is uncertain and will depend on the type of future scenario that emerges. For example, issues may be negotiated locally with environmental benefits traded against other functions of urban watercourses.

There is also uncertainty in the prediction of the morphological response and in terms of assessing the issues and the impact of an evolving (greening) of the urban watercourse corridor. The introduction of environmental-protection technology within the urban area and its acceptance is also uncertain.

Figure B3 **Impact on the environment**

Driver

B5: Urban Watercourse Conveyance, Blockage and Sedimentation

Driver group: Urban conveyance systems and processes
Type: Pathway

Definition and operation

Processes associated with surface flow above ground in natural watercourses and man-made systems, including performance, maintenance and operation.

This driver has important implications: it influences urban watercourse conveyance, flow dynamics and flood storage. For example, changes in river-channel morphology and sediment supply that lead to the adjustment of channel attributes (cross-sectional shape, bed roughness and so on) will affect flood storage and flood conveyance. Similarly, changes in channel vegetation and/or micro-morphology influence the velocity distribution and the turbulence levels in flows. Vegetation changes seasonally, through maintenance and in response to climate change. Floods or prolonged periods of low flow control micro-morphology.

The natural path of urban watercourses, and their water conveyance, is often changed within the urban area by man-made structures. These structures include culverts, channel realignment, structures for flow measurement, bridge piers and outfalls from drainage systems. Structures such as culverts have a finite hydraulic capacity. Hence, should fluvial flood flow exceed the design capacity of a culvert or should the hydraulic performance of the culvert be impaired, the excess flood flow usually has no alternative other than to inundate the catchment surface of the intra-urban area. Putting natural watercourses in culverts in the intra-urban area may therefore be seen to enhance flood risk. These structures also interfere with the natural drainage path and may cause sediments to build up, eventually leading to a full or partial blockage. Other debris deposited with the urban systems may also increase the potential for blockage and impair performance of outlets to the urban drainage system.

Chapters 3 and 5 suggest that under the base line assumption (in which the level of expenditure to maintain fluvial and coastal flood defence remains constant), the risk of defence failure would grow, with the potential for fluvial systems to overtop defences and flood urban areas. This, combined with anticipated changes in flood risk due to changes in the hydraulic regime within the fluvial system – increased flows due to climate change and the potential for reduced conveyance – will also increase the risk of inundation flooding within the urban area. In addition, increased water levels in rivers will impair drainage outfalls with the consequent back-up of fluvial flows into urban drainage systems. This will impair the performance of urban systems, and surface flooding may result.

In the case of coincident flooding the combined influence of inundation fluvial flood flows (often containing contaminated sediment and effluents from sewers), together with increased volumes of surface runoff that cannot enter the underground drainage system will increase flood risk with a corresponding increase in health risk.

Interactions with other drivers

There are strong interactions between the driver Urban Watercourse Conveyance, Blockage and Sedimentation and the runoff drivers, which determine the extent of the flows that the urban watercourses have to carry. There is also an interaction with Environmental Regulation, as practices adopted to improve the environment of the river corridor may have a significant impact on conveyance and in-river processes.

The sewer conveyance to the natural watercourse has obvious interactions, both in terms of flow magnitude and pollution quality. The deterioration of structural assets, for example, culverts, may also occur, with the consequent interaction between Intra-Urban Asset Deterioration and Infrastructure Impacts. The need for the river environment to be safe at the time of flood events interacts with the expectations of Public and Science and Technology as a receptor.

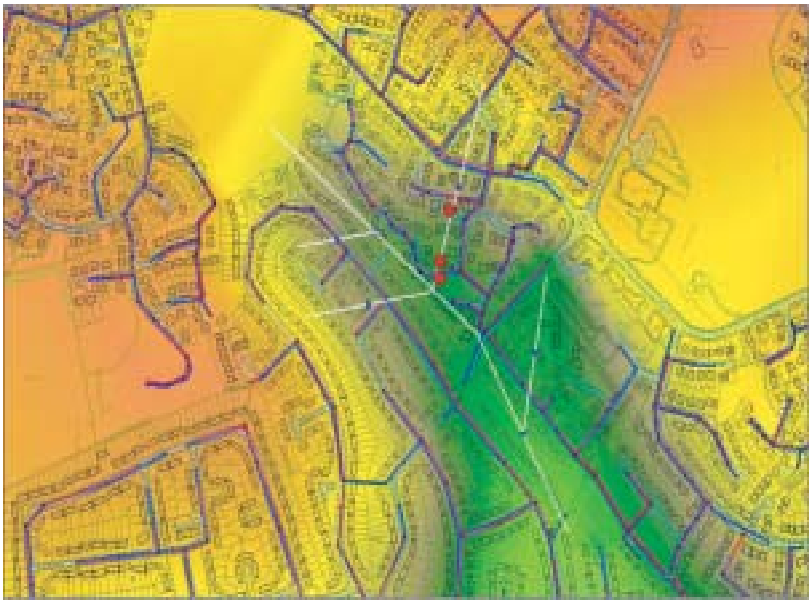
Effects on flood risk

Prediction of the changes in flood risk within the urban watercourse conveyance system is in its infancy due to the significant uncertainty in understanding the changes and interactions between the hydrology, the sediments and the morphology. Individual components of the processes have been attempted and these are usually modelled within the framework of a geographic information system (GIS) (see Figure B4). GIS maps of the impact of the individual component processes may be layered but further work is required to address their interaction.

Uncertainty

There is considerable uncertainty across all climatic and economic sectors associated with Urban Watercourse Conveyance, Blockage and Sedimentation. This is primarily due to a lack of knowledge of significant interactions.

Figure B4 **Geographic information systems can model the urban watercourse conveyance linked to the urban systems**



Driver

B6: Sewer Conveyance, Blockage and Sedimentation

Driver group: Urban conveyance systems and processes
Type: Pathway

Definition and operation

Processes associated with below-ground flow in man-made drainage infrastructure, including performance, maintenance and operation.

Sewers are the principal assets for the conveyance of surface-water runoff in the urban areas of the UK. In older urban areas, the sewer systems are mainly combined, with domestic and industrial effluents and rainfall-runoff conveyed in the same pipes. Combined sewer overflows (CSOs) are constructed to relieve the system of the excess flows that cannot be accommodated by the downstream sewers or the treatment works, thereby reducing the risk of surcharge and surface flooding in the catchment upstream of the CSO. Similarly, storage tanks are commonly employed to retain effluents for subsequent treatment. More recently, and particularly on new or fringe developments, separate drainage systems have been constructed. One set of pipes conveys foul effluents directly to the treatment works, while a second set of pipes discharges surface water directly to inland or coastal receiving waters.

Many components of sewer conveyance, blockage and sedimentation influence flood risk. There is an interaction between the surface overland flow that attempts to enter the system, the amount of groundwater infiltration, the hydraulic capacity of the underground system (inlets, pipes and outlets), the structural condition of the system and the interaction with the urban watercourse conveyance system. For example, the performance of an intra-urban area drainage system may be influenced by the performance of the fluvial drainage system in two ways:

- Hindered performance when enhanced fluvial flows inundate the discharge outlets of the sewer system, causing a back-up in the sewer system. The consequence of such a back-up depends on its extent and the layout and elevation of the sewer system. The result may be to flood basements and catchment surfaces with sewage alone or with a mixture of sewage and fluvial flows. Low-lying areas of the intra-urban area are particularly prone to this type of flooding.

- Inundation of the intra-urban catchment surface due to the failure, overtopping or bypassing the flood defences of the fluvial system. This inundates the sewer system which fills and becomes inoperable due to the extremely slack hydraulic gradients. As a consequence ponding occurs on the catchment surface.

Within the urban area, fluvial flooding of urban surfaces with dirty and contaminated sediments will also have effects on health.

There may be similar impacts in the intra-urban areas adjacent to coastal and estuarial environments where the height of surges or the overtopping or failure of coastal defences may hinder the performance of the sewer system.

Co-incident flooding is also a major driver. It combines the influence of pluvial and fluvial flooding, and hence presents the worst-case scenario for the impact on the urban area.

Below-ground drainage systems are watertight when constructed, but few remain completely watertight over time. Minor movement at joints, or cracks – caused by ground movements, for example – can create leaks in the pipe system (see Figure B5). Hence, if the groundwater table is above the crown of the pipe, groundwater will infiltrate into the sewer.

These infiltration flows will, in effect, reduce the capacity of the sewer systems to accept the surface flows at the time of storms. If the infiltration is significant – as it can be in some more rural catchments or where the sewer system is in poor condition – it could reduce a sewer's capacity to take storm runoff by between 30 and 50%. This reduction could seriously increase the likelihood of sewage flooding and spills to watercourses. This will increase the risk of flooding.

The future will see the increased use of water recycling systems, water re-use systems, Sustainable Urban Drainage Systems (SUDS) and local flood prevention intervention structures, for example, temporary barriers. Such measures could reduce flood risk.

Interactions with other drivers

Precipitation drives the volume of runoff, with the consequent impact on the urban drainage conveyance system as a receptor. Changes to the urban infrastructure in the form of the application of Science and Technology influence flow paths with a subsequent impact on the extent of internal flooding of property and external flooding of the ground surface. The subsequent discharges from sewer systems into receiving waters affect the environment, ecosystems and habitat, with the need for regulation and management to meet the needs of the regulator and the public.

Effects on flood risk

The hydraulic performance of well-defined underground drainage systems is reasonably well understood. A suite of mathematical models, such as the InfoWorks package from Wallingford Software, are available for predicting their behaviour. There is a need to calibrate and verify these models and procedures. Modelling of water quality and the role of sediments is less well understood.

Models of infiltration inflow are under development, as are models of surface overland flow to better predict flood-flow paths and the extent of inundation. Models are available to predict the impact of sewerage discharges on the quality of the receiving stream, but models are still under development that take into account the interaction of the sewer and the river system, for example, the influence of the receiving water restricting the sewer outlet.

Uncertainty

There is considerable uncertainty associated with all aspects of urban conveyance systems, primarily due to the strong but unknown interaction between the above- and below-ground components of the system and how these influence the appropriate processes. Precipitation is the key driver. It is not yet clear what the impact will be of climate change on the duration and intensity of storms that are appropriate for modelling urban drainage systems.

Figure B5 **Sewers start their life free of cracks and leaks, but over time ground movement can create leaks through which water may enter from the surrounding ground. The result can be to reduce the pipe's water carrying capacity during storms.**

Driver

B7: Impact of External Flooding

Driver group: Urban conveyance systems and processes
Type: Pathway

Definition and operation

Loss of conveyance and serviceability in below-ground drainage systems due to flooding from external sources.

External sources can lead to flooding in an urban area for many reasons (see Figure B6). A common source of flooding is when the urban area is downstream of the flood path from the surrounding peri-urban area. Precipitation falling in this area may reach the urban area through overland flow routes across fields, in ditches, and along tracks and highways that eventually lead to the urban drainage system. This surface runoff can flood the intra-urban area because there is no sewer system where the surface runoff enters the intra-urban area, or because the flow may not be able to enter the sewer system due to insufficient or inadequate gulley (or other) entry points, or the sewer system is hydraulically overloaded. This results in external flooding that subsequently impairs the natural gravitational performance of the urban drainage system, potentially increasing the volume of the flood flow that can create external flooding.

Similarly, overtopping of flood defences, either fluvial or coastal, will often inundate the urban surface. Such inundation will impair the performance of the underground drainage system. The relationship between the extent of inundation and impairment of the underground drainage system is not fully understood.

Interactions with other drivers

Precipitation is a primary driver that influences the extent of the inundated flood area: this ultimately generates the volume of runoff with the consequent impact on urban flooding. There is high interaction with the sewer conveyance system as its available hydraulic capacity determines the extent of the likely external flooding.

Effects on flood risk

Current methodologies to predict the impact of external flooding are extremely limited. Little is known about how the runoff from the peri-urban area affects the performance of the urban drainage system. There are attempts to use layered GIS methodologies that show the interaction between surface topography, urban building form and the underground drainage system. This work has yet to report.

Uncertainty

There is considerable uncertainty in the prediction of the volumes of the flood water that will enter urban areas and in the extent of the inundation. The interaction between the performance (available hydraulic capacity) of the sewer system and the extent of the urban flooding is also uncertain.

Figure B6 **Impact of surface flooding**

Driver

B8: Intra-Urban Asset Deterioration

Driver group: Urban conveyance systems and processes
Type: Pathway

Definition and operation

Changes in the performance, condition and serviceability of urban drainage assets (ageing, performance wear and tear and rehabilitation management).

The performance of assets, and asset failure, also affect flooding of the urban area.

Population growth, increased urban development, increased wealth and an apparent growing need to occupy flood-prone areas has increased flood risk within the urban area. The Office of Water Services (OFWAT) records flooding incidents from sewers in one of three registers:

- DG5 – Properties at risk of flooding more than twice in 10 years at the end of the year.
- D10 – Properties at risk of flooding more than once in 10 years (but less than 2 in 10) at the end of the year.
- OFA (Other Flooded Areas) – Flooding that only affects areas outside properties, for example, gardens, footpaths, roads and fields.

Properties at risk are defined as properties that have suffered or are likely to suffer flooding from public foul, combined or surface water sewers due to overloading of the sewerage system more frequently than the relevant period, either once or twice in 10 years.

In 2000-1, OFWAT reported that 7,100 properties in England and Wales suffered internal flooding from sewers, which is a risk of 0.0315%. However, of these properties, some 55% of flooding incidents were due to causes other than hydraulic overload. These figures do not include internal flooding due to severe storm events.

Currently, at the time of flood events, the levels of service and levels of performance that are achieved by the urban drainage systems at the time of flood events is unclear. There is therefore a need for better indicators of serviceability for sewerage assets (OFWAT/EA, 2001). Of particular relevance to the intra-urban area is the need for performance measures that describe the incidence of flooding from sewers due to:

- Sewer blockages.
- Sewer collapses.
- Presence of sewer sediments.
- Maintenance and equipment failure.
- Pumping station operation.
- Inadequate hydraulic pathways.
- Hydraulic inadequacy of sewer pipes.

At the present time, therefore, there is no consistent way to assess the flood risk due to asset performance. This shortcoming is further compounded by the need to understand the influence of rehabilitation strategies and of structural and non-structural interventions.

Interactions with other drivers

There is a strong interaction between performance, condition and serviceability with regulation and the need for effective asset management. There is also a strong interaction between Science and Technology, both as a pathway and as a receptor. Stakeholder Behaviour and Public Attitudes and Expectations also interact strongly due to the need to maintain a quality service at an economic cost, taking due regard of all social, economic and technological costs.

Effects on flood risk

Techniques are under development to provide better understanding of the link between the performance, condition and serviceability of assets. The primary strategy is to examine historical data associated with each performance driver, and to develop predictive models to assess how the performance of assets will change. These models must take account of interventions: techniques are under development to optimise interventions at least cost. Such research includes analysis of data for the frequency of collapse as a function of pipe age in pipes of different materials (see Figure B7). Figure B8 demonstrates the impact of a sewer collapse.

Uncertainty

In the intra-urban area, the uncertainty associated with asset deterioration is a function of the climatic and socioeconomic scenarios. Where due regard is taken of the need to maintain existing assets, there is medium uncertainty as to how future flood risk will change; but for scenarios where there is less consideration for such assets, or where the climate scenario is one of high emissions of greenhouse gases, there is considerable uncertainty.

Figure B7 **Relationship between collapse frequency and age for concrete, vitrified clay and brick pipes**

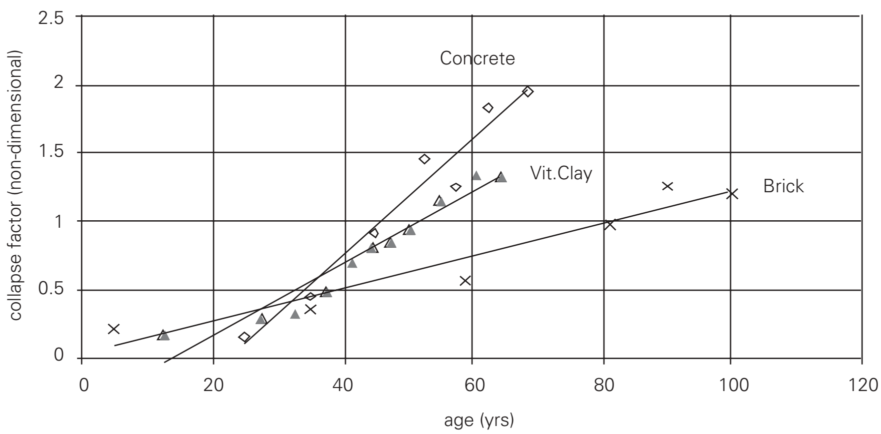


Figure B8 **Impact of sewer collapse**

Appendix C

Pathways of flooding outside the floodplain

Introduction

It has been observed that significant flood impacts may be experienced in areas that are neither in the indicative floodplain maps nor associated with urban flooding problems (e.g. urban drainage systems). The category covers a large number of diverse flood processes, including:

- Flooding that occurs at the boundaries of the indicative flood zones.
- Flooding due to rises in the groundwater table in permeable catchments.
- Flooding arising at the urban-rural interface linked to rapid runoff from agricultural land (sometimes referred to as 'muddy flooding').
- Flooding due to small-scale infrastructure failure (e.g. bunds, ponds etc.) in rural areas.
- Flooding related to larger-scale infrastructure (e.g. the canal system), which is included in statutory flood-risk analyses to a varying degree.

There is no generic mode of operation for disconnected flooding. However, the mechanisms share a number of important characteristics:

- Flooding outside the indicative floodplain impacts on a large number of people with a wide geographical extent.
- The causes are geographically specific (e.g. linked to isolated springs; to locally specific instances of small-scale infrastructure failure).
- Impacts may be manifest in very different ways (e.g. as rising groundwater levels in the cellars of properties; in surcharging culverts that make rural roads impassable but where passage along roads is still attempted by motorists; as muddy surface runoff from fields into properties).

This makes the identification of a generic mode of operation difficult, but groundwater flooding, muddy flooding and infrastructure issues are explored here.

C1: Groundwater flooding in permeable catchments

Definition and operation

This is flooding that is associated with groundwater table fluctuations and which can lead to low-magnitude and long-duration flood events in permeable catchments where groundwater fluctuations are significant.

Groundwater flooding is associated with fluctuations in the groundwater table in major aquifer outcrop areas. Groundwater is generally distinguished from saturated throughflow in soils by being mainly located in bedrock or sediment (e.g. alluvium) and involving slow flow rates. It is primarily associated with permeable bedrock/sediment and hence sedimentary rocks (e.g. limestone, sandstone), although some sedimentary rocks may still be too impermeable to be associated with groundwater. Rocks that hold groundwater at atmospheric pressure are called aquifers. An unconfined aquifer is one that intersects with the ground surface. A confined aquifer is found between aquicludes, which are bodies of water holding rocks that transmit very little water. However, (hydrostatic) pressure within a confined aquifer can force water upwards to form an artesian spring.

The dynamics of groundwater are controlled by: recharge, as defined by the excess of rainfall over evapotranspiration losses; and flow within aquifers as controlled by a piezometric surface. The piezometric surface is a product of the small-scale topography and geology of the system as well as larger-scale gradients in rainfall and recharge. The main loss of water from the groundwater system will be either linked to artesian springs associated with confined aquifers, or over the ground surface where unconfined aquifers intersect the ground surface. As the amount of water within a groundwater system increases: (1) the pressure within confined aquifers may increase, increasing the flow out of and possibly the number of artesian springs; and (2) the elevation of the water table within unconfined aquifers will rise, increasing the extent to which it intersects with the ground surface. The prime loss of groundwater is through either streams fed by unconfined aquifers or artesian springs, and this can be significant in maintaining baseflow in some river catchments.

During the late spring, summer and early autumn months, evaporation and transpiration losses generally exceed rainfall. Baseflow may continue from some unconfined aquifers and artesian springs. The net result is drawdown of water tables. Groundwater replenishment is generally confined to the late autumn, winter and early spring, when soil moisture deficits are lower or even negative, and recharge occurs. Thus, the magnitude of drawdown in any one year and the magnitude of recharge will be driven by the combination of temperature and precipitation over the year. Low levels of drawdown (e.g. due to reduced evapotranspiration losses or high precipitation during the drawdown season) or high levels of recharge (due to high levels of rainfall) can both cause water-table rise and groundwater flooding. It should also be noted that there can be persistence from one year to the next: i.e. there can be progressive increases in groundwater levels over a period of time, linked to a series of years with small net positive recharges. This persistence means that conventional linkage of rainfall and annual flood series in groundwater dominated systems need to be undertaken with caution. There is now guidance (e.g. CEH) for flood estimation in permeable catchments.

Figure C1 shows examples (from the CEH Hydrological Yearbook for 2000). The dotted line is the long-term expected average, the white band the range of water levels and the black line the actual water levels for 1996 to 2001. These diagrams are important for a number of reasons. First, they emphasise the very great range in groundwater response modes. Some systems (e.g. Killyglen) are very sensitive to fluctuations in rainfall, with water levels responding more rapidly. These types of systems are most likely to result in short-term groundwater flood events. Dalton Home (Figure C1), in contrast, is associated with long-duration high-ground water levels: wherever these levels intersect the local topographic level, there will be sustained discharge of water. These types of situations may lead to prolonged flooding problems (e.g. long-term road closures, flooded cellars) that are very different to both the very short term, high magnitude flood events associated with pluvial flooding in urban areas and also the relatively short-term high-magnitude flood events associated with fluvial flooding from main rivers. Finally, many of the boreholes (e.g. Dalton Holme, Dial Farm) show persistence, with progressive rises in groundwater levels across many years.

Given the above, we can summarise the operation of groundwater flooding. It is associated with longer-term (as compared to other types of flood events) fluctuation in water tables in autumn, winter and spring periods when either: (1) drawdown rates in the previous summer have been relatively low (due to higher than average effective rainfall in the summer); or (2), and most importantly, recharge rates have been relatively high. The nature of the flood risk depends on the nature of the aquifer system, producing both short-duration and long-duration flood risk. Floods associated with long-duration flood risk are very different to those associated with either pluvial or main-river fluvial flooding.

Figure C1 **Water levels from selected boreholes between 1996 and 2001 (black lines), long-term averages (dotted lines) and maximum and minimum values (defined by the white band). Source: CEH 2001**

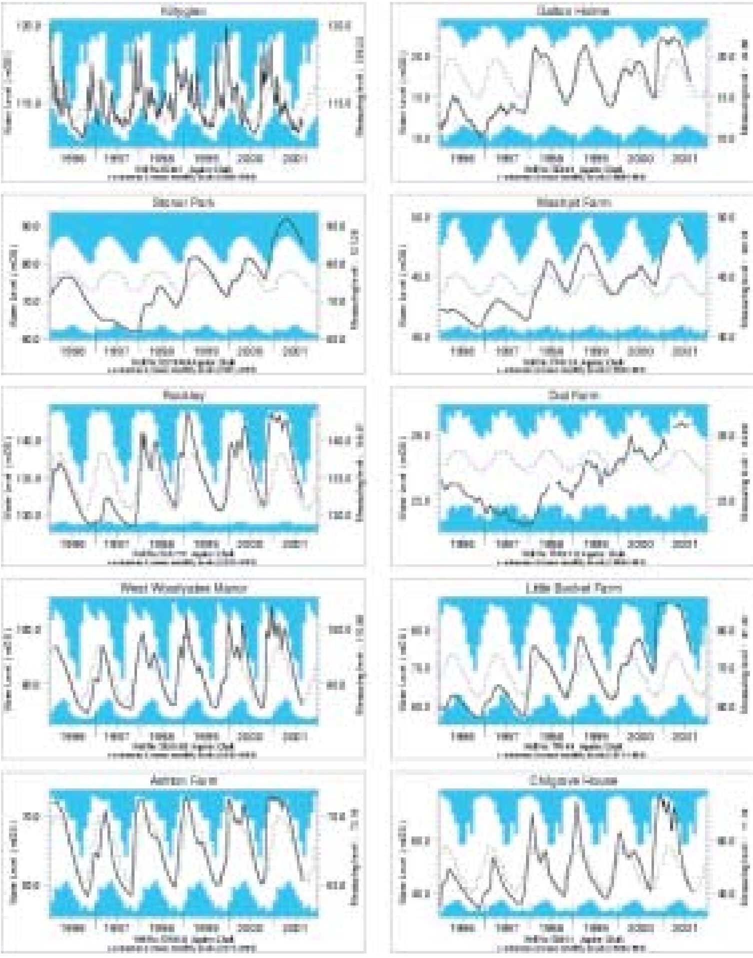


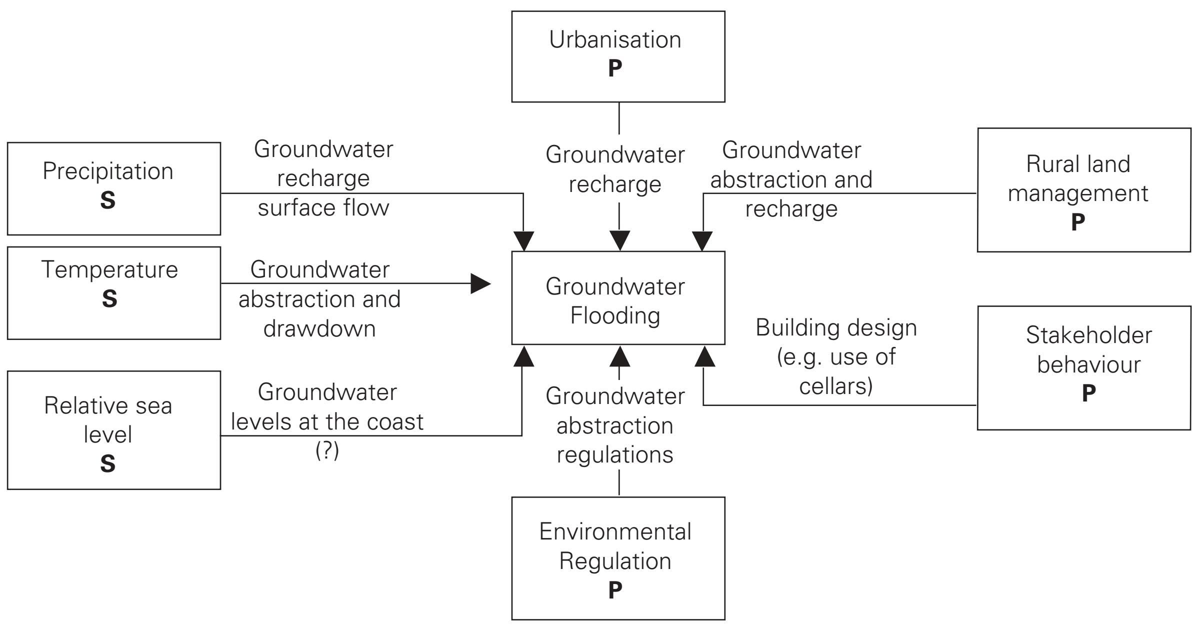
Figure C3 **Groundwater flooding in Hambledon in 2000/1. Source: BBC**

Interactions with drivers

Figure C2 summarises the sources and pathways that will influence groundwater flooding. Precipitation, and notably the magnitude of groundwater recharge (i.e. total annual precipitation, autumn and winter precipitation) is the prime control on groundwater recharge and hence the precipitation source is crucial. The temperature source also matters as this determines the net water balance available for groundwater recharge as well as the water demand that may lead to groundwater abstraction. Thus, in climate-change terms, future groundwater flooding will relate to the balance between changes in precipitation and increases in temperature.

Both the Urbanisation and Rural Land Management pathways appear as influences upon groundwater flooding, but most probably as secondary influences to the prime climatic drivers. Urbanisation within a catchment may impact on groundwater abstraction but, more importantly, will control the partitioning between surface runoff and groundwater recharge. Rural Land Management appears for the same reasons: it may influence groundwater abstraction and also recharge. Stakeholder behaviour matters as there is evidence that the form of building and infrastructure adoption can influence the flood routing process. The case example for groundwater flooding illustrates how the magnitude and frequency of flooding in the village of Hambledon may have been exacerbated by road construction. Environmental regulation is potentially a very important pathway for groundwater flooding as a result of regulatory controls on groundwater abstraction. Such regulations may reduce the volume of groundwater storage and hence modify flood risk.

Figure C2 **Groundwater flooding in relation to sources and pathways**



In relation to receptors, groundwater flooding impacts can become more significant as a result of a range of changes in socioeconomic processes. The progressive increase in consumable goods may require people to make use of all the space within a house, with more goods stored in cellars and an associated link to the Buildings and Contents impact receptor. Growing pressure on space for housing may encourage the conversion of existing properties, including ground-floor and below-ground rooms that are most at risk from groundwater flooding. Thus, there is a link to the Urban Impacts receptor. There are many cases of where groundwater flooding impacts upon Infrastructure. As groundwater impacts can be of especially long duration, these impacts may be expensive.

Case example: groundwater flooding in Hambledon, Hampshire

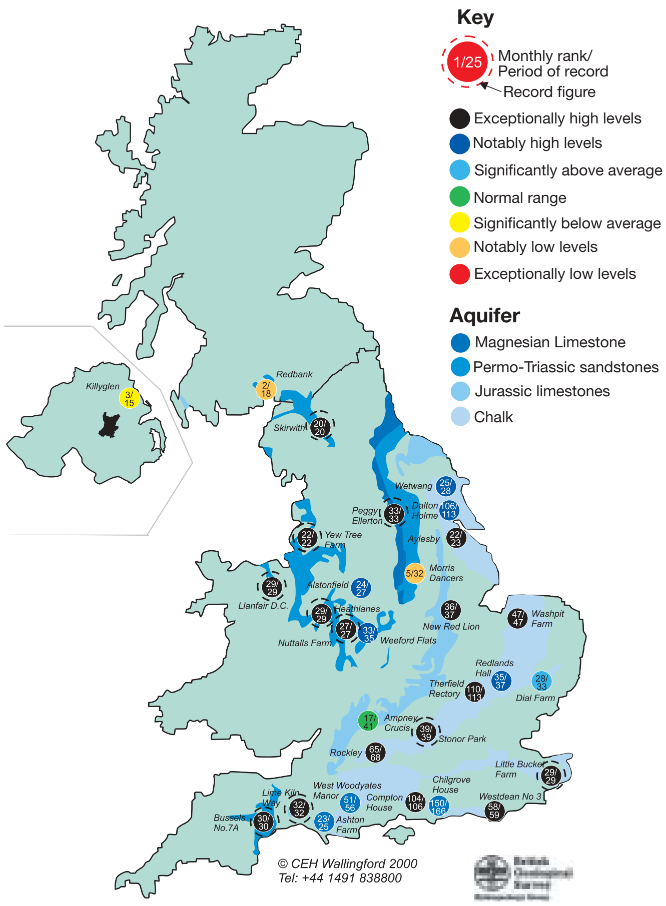
The nature of groundwater flooding is well illustrated by the case of Hambledon in Hampshire (Posford Duvivier, 1995, 2001). Hambledon experiences regular periods of severe groundwater flooding (e.g. Figure C3). The village is in the South Downs in a valley centred on the Upper Chalk group. The upper chalk is relatively impermeable. However, there are extensive fissures in the material which provide storage and routing for the passage of groundwater. Groundwater levels respond rapidly to precipitation and there is a regular seasonal variation in water-table levels, in the context of chalk permeability and local topography. Generally, during periods of prolonged heavy rainfall (but not necessarily intense rainfall), there is a progressive rise in the water table within the chalk aquifer. Groundwater starts to have an effect when the water level reaches 50 m ODN (Ordnance Datum Newlyn). When water levels rise above this, springs appear at the base of hillslopes and cellars begin to flood. Groundwater flooding occurred in 1960/1, 1962/3, 1974, 1974, 1977, 1988, 1990, 1994, 1995, 2000/1, with the most severe events in 1994 and 2000/1.

In the case of Hambledon, the problem has been exacerbated by the filling in of a ditch and raising of road levels which is preventing some cellars from draining. The ditch used to run the length of Hambledon to accommodate ephemeral flows through the village. This has been piped and filled in through time, with hardstandings over the ditch. The groundwater flood event in 1994 was estimated to cost £250,000 to the Emergency Services and about the same in private household damages (in a village with fewer than 1,000 people) (Posford Duvivier,1995).

Driver changes and flood risk impacts

The main issue in relation to groundwater flood risk is the potential effect of the climate-change sources, under all Foresight scenarios. In general terms, increasing temperature should reduce groundwater recharge, especially if this increases water abstraction due to greater crop demands. However, changing precipitation patterns may also influence groundwater recharge. Of particular concern will be: (1) whether or not climate change increases the inter-annual variability in precipitation totals; and (2) to what extent years in which low levels of summer drawdown coincide with high levels of recharge in the subsequent autumn and winter. These changes will be compounded by other driver changes and there is a long term risk that the over-abstraction of groundwater during the 20th century is now being reversed (due primarily to reduced pumping), leading to long-term rises in groundwater levels in some situations. Figure C4, for instance, shows the trend in borehole levels at Trafalgar Square. If these trends continue, and there is evidence from a number of deeper groundwater systems that they are, this implies serious potential underground flood risk in relation to infrastructure (e.g. foundations, tunnels etc.). Thus, in relation to climate-change drivers, both land management and regulatory impacts on groundwater abstraction may not only increase flood risk but do so in ways that are very different to pluvial and fluvial flooding.

Figure C5 **Main UK aquifers and selected groundwater monitoring boreholes Data refer to January 2001 and indicate high levels that were responsible for serious groundwater flooding. Map supplied by CEH Wallingford**

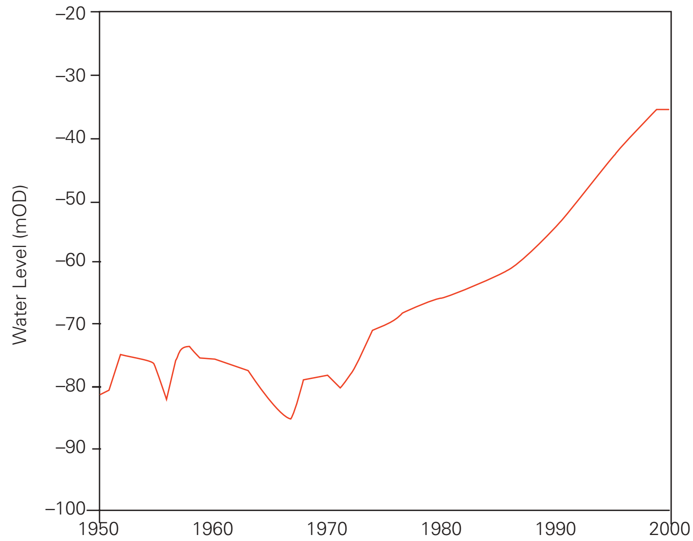


The rankings are based on a comparison of current levels (usually a single reading in a month) with the average level in each corresponding month on record. They need to be interpreted with caution especially when groundwater levels are changing rapidly or when comparing wells with very different periods of record. Rankings omitted where they are considered misleading.

Uncertainty

Uncertainties associated with this aspect of the flood system are high and arise for a number of reasons. First, the exact nature of climate-change impacts, and the relatively subtle impacts of increases in recharge due to precipitation changes and decreases due to evapotranspiration changes could move changing flood risk due to groundwater either side of a better/worse threshold. Of particular concern is whether years similar to 2000/1 occur more frequently, not so much in terms of extreme flood events, but more generally wet summer-autumn-winter periods, which are what leads to sustained recharge. The second area of uncertainty is associated with the regulatory environment and issues of water abstraction. This is highly sensitive to the Foresight scenario adopted as this controls the regulatory framework as well as the agricultural system's demand for water. The third area of uncertainty relates to geographical variation in the nature of the groundwater system.

Figure C4 **Rising borehole levels at Trafalgar Square since 1950. Source CEH 2001**



Native parameter

Application of groundwater flooding risks within a strategic flood risk assessment will need some modification. In theory, it can be represented by a change in the standard of protection (i.e. a change in the magnitude-frequency of groundwater flooding). However, operationalising this needs some thought, as the risk occurs away from the designated main rivers and their floodplains. We do have a good knowledge of where aquifer outcrops may be found (e.g. Figure C5) and there is generally good local knowledge of both local aquifer characteristics and springs. Thus, it may be feasible to use this information in a strategic analysis.

C2: Muddy floods

Definition and operation

These floods are caused by overland flow generated in rural areas where the overland flow connects directly with houses and other infrastructure, rather than through the conventional river network. They do not necessarily need to involve soil erosion (which is what makes them muddy) but there is a strong link with runoff from fields and small tributaries that also results in soil erosion.

These types of flood events are generally associated with rainfall events that result in significant amounts of overland flow and surface routing of that flow to roads and into houses without any reinfiltration into the ground surface. Evidence suggests that they can occur due to both infiltration-excess and saturation-excess overland flow (Boardman 2003). Infilitration-excess overland-flow processes occur either due to extreme-intensity rainfall events or due to soil-surface processes (e.g. crusting) that leads to a reduction in surface-infiltration rates. Boardman noted that soil crusting can occur rapidly in autumn if there is heavy rainfall, and that this may be exacerbated by other aspects of land management such as compaction due to wheelings and rollings. Field observations show that crusting may be significant enough to prevent any rainfall reaching the soil-bedrock interface, with almost all the rainfall becoming overland flow (Boardman 2003). Soil crusting is a process that tends to occur on bare soil, and Boardman observes that even during major storms, runoff from grassed area is minimal. However, saturation-excess overland flow can also occur, especially in certain topographical locations (e.g. locations of topographically-driven flow convergence) and/or if the soils are thin, and storage capacity is low. There is a linkage here to groundwater rise, which can also result in saturation-excess overland flow.

Chambers and Garwood (2000) identify the conditions that may lead to muddy floods: these are sandy and silty soil textures; landform; cropping system; and rainfall. Of particular concern are winter cereals and Chambers and Garwood estimate that around 40-65% of fields with this land use experience surface soil erosion (and hence surface flow) of some sort. Boardman and Evans (1991) estimated that the transition from grassland to autumn-sown cereals had lowered the threshold at which flooding took place from 1 in 100 years to 1 in 3 or 4 years in one location in the South Downs. There is also a strong link to land management: Evans (1990) noted that tramlines, wheelings and downslope cultivation were implicated in 84% of observed erosion events.

However, while rainfall amount is a key factor in muddy-flood generation, both low-intensity and high-intensity rainfall events can result in surface runoff and erosion, depending on the state of the soil surface, local topography, soil type and the nature of land management (Chambers and Garwood 2000; Boardman 2003). For instance, Chambers and Garwood (2000) report that 96% of erosion events studied involved only > 10 mm/day provided intensity was > 4 mm/hour. Prolonged rainfall, even at low intensities, can generate surface runoff (e.g. Kirkbride and Reeves 1993) if other conditions are right.

The main issue in relation to these types of flood events is whether or not the generated overland flow can connect to locations where it can do damage. This is partly determined by patterns at the within field scale and field arrangement scale (i.e. in relation to the land-management unit). It is also strongly topographically and land-use defined. This was reported by Evans and Boardman (2003) who show that the risk of muddy floods reaching a housing estate in the South Downs was dominated by the extent to which generated runoff could connect fully along the associated flow-path length.

In summary, muddy floods are associated with either rainfall or land surface characteristics that are sufficient to generated significant, connected overland flow, and hence flood risk, without flows entering the main river. Most evidence in this respect has been directed at muddy floods, where there is a strong land use and land management linkage. Such floods may occur in other environments (e.g. in catchments with a very short response time in upland areas).

Interactions with drivers

Figure C6 shows that one of the prime drivers of muddy-flood risk is precipitation, with observations that suggest that the amount of rainfall, its intensity, and its timing can all contribute to muddy-flood generation. Of particular importance is the coincidence of large rainfall amounts with the drilling of winter cereals which commonly takes place in early autumn. Thus, climate changes that increase autumn precipitation may increase the incidence of flood risk. However, and unlike analyses for the effects of rural land management on main-river flood risk, there is a very strong impact from the land-use and land management drivers. There is strong evidence that the incidence of muddy floods in the South Downs can be related to the adoption of winter cereals during the 1980s. Similarly, land management, and notably tramlines, wheelines and ploughing that does not follow contours can significantly increase muddy-flood generation. As a result, both the Stakeholder Behaviour (e.g. farmer decisions over good land management) and Environmental Regulation (e.g. Common Agricultural Policy reform; Environmentally Sensitive Area Schemes) drivers that impact upon land use and land-use management will also impact upon muddy floods.

Case example

A good example of flood risk caused by muddy floods is provided by the Sompting catchment, South Downs, West Sussex. The Sompting catchment comprises a series of dry valleys extending to 211 m above mean sea level. The geology is soft, pervious chalk (Evans and Boardman 2003) with shallow soils < 0.30 m deep). The eastern South Downs have witnessed 138 flood damage incidents in the period 1976 to 2002 (Boardman *et al*. 2003a) and all of these refer to runoff from agricultural land and the majority where the land use involves winter cereals. Boardman *et al*. (2003a) report that the area of the catchment drilled to winter cereals increased from about 15% in 1975, to around 35% in 1981 and c. 60% by 1988 and 1991. Boardman and Evans (1991) estimated that this transition from grassland to autumn-sown cereals had lowered the threshold at which flooding took place from 1 in 100 years to 1 in 3 or 4 years in Sompting and houses have been flooded in 1980, 1987, 1990-1 and 1993-4. Flooding was significantly reduced in the catchment by 2000-1 due to land-use change (see Phase 3 technical report).

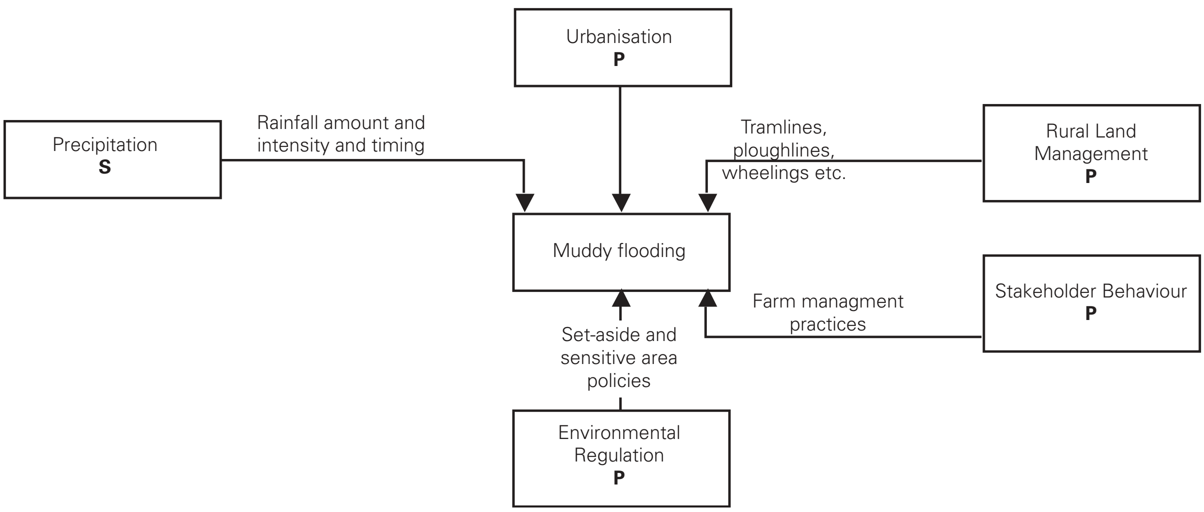
Driver changes and flood risk impacts

The driver changes that matter in relation to muddy flooding can be grouped under two main headings. The first is climate-change-related, and involves possible increases in the amount and/or intensity of early autumn rainfall. This would increase flood risk. The second group relates to the direct effects of Urbanisation and Rural Land Management and the indirect effects of Stakeholder behaviour and Environmental regulation. This group seems to be the prime driver of muddy-flood risk generation. It is strongly sensitive to the Foresight scenario adopted as a result of the changing degree of regulatory influence and prioritisation of agriculture between scenarios.

Uncertainty

There remains a degree of scientific uncertainty regarding the generation of muddy floods. While those associated with the chalk downs of southern England, the same level of analysis has not been conducted in other parts of the UK. For instance, it may not be an especially important source of flood risk away from the more developed south coast, where housing has been located very close to areas of muddy-flood risk. This uncertainty could be reduced by a more in-depth analysis of insurance industry returns in relation to disconnected flooding, in comparison with other disconnected flood mechanisms. This is mirrored in issues regarding the importance or otherwise of land management practices besides winter cereals. Uncertainty also arises in relation to the possible impacts of regulatory change and stakeholder behaviour.

Figure C6 **Muddy flooding in relation to sources and pathways**



Native parameter

As this is a disconnected flooding problem, there is no explicit method for including it in the strategic risk assessment described in Chapter 4. However, if areas where this is a flood risk could be identified, changes in muddy flooding could be expressed as a change in the standard of protection.

C3: Floods related to infrastructure and ordinary watercourses in non-floodplain areas

Definition and operation

These flood incidents are commonly associated with extreme rainfall events but are linked to infrastructure issues in rural areas. It is a diverse label ranging from the failure of small ponds and bunds through to flooding associated with the network of waterways, where these are not designated as main river and/or not incorporated in flood-risk mapping studies – a very broad category of flood characteristics.

Unlike other instances of disconnected flooding, these floods are predominantly related to extreme precipitation events. There is also a strong overlap with intra-urban flooding. However, there is a number of situations where isolated or small groups of properties in rural areas can experience flooding away from the main river due to infrastructure failure or management issues (e.g. ordinary watercourses that are not designated as main river and hence are not included in statutory flood-risk mapping). Infrastructure failure can take a number of forms including:

(1) Culvert collapse, blockage or surcharging that causes flow to travel overland according to local topography, including the diversion of flow onto roads and hence into properties, damage to vehicles, and, in extreme cases, loss of life.

(2) Drain blockage or surcharge in non-urban areas, especially those that contain sewerage, or linked to pluvial flooding.

(3) Any flooding that occurs in ordinary water courses, drains or ditches.

(4) Failures of small ponds or bunds.

(5) Failure of pumps associated with internal drainage activities.

(6) Flooding linked to the canal network, where either flow into the canal exceeds canal capacity, or where river levels are so high that over flow into the river from the canal cannot occur (this type of flooding is variably dealt with in national-level flood -isk mapping).

The main characteristic of all of these causes of flooding is that they are associated with ordinary watercourses and/or watercourses that come under the responsibility of district councils, internal drainage boards, individual land owners, the water utilities, Railtrack, the Highways Agency or county councils (in relation to roads) and British Waterways. Many of the associated issues will have been dealt with in part under the intra-urban section of this project. These flood events are problematical in relation to flood risk as they are widely distributed, with many responsible authorities who may not know of the locations of all of the infrastructure for which they are responsible. There is also the issue of ageing infrastructure which may contribute to the problem. However, some of the responsible authorities do have risk-management procedures in place in relation to flooding: British Waterways, for example, was actively involved in the management of the 1998 and 2000 floods (Simm *et al*. 2002). The same is true of local authorities.

Interactions with drivers

As a result of the complex and variety of causes of flooding in this category, summarising interactions is difficult. However, the key driver is Precipitation, with almost all of the flood types listed above linked to extreme precipitation events.

Case examples

There is a very large number of these that can be gleaned from searching databases of local newspapers. In June 2000, a major summer storm event caused a pond failure in the village of Carleton-in-Craven, North Yorkshire. In November 2000, extensive parts of the town of Skipton, North Yorkshire, had to be evacuated due to a potential canal failure caused by the towpath being undermined by a tributary of the River Aire. Had the canal failed, the properties that would be affected (about 700 in total) were not in the indicative floodplain.

Uncertainty

These flood types are highly uncertain as they are widely distributed geographically and take on a very wide variety of forms. We know very little about how different flood damages are apportioned between the types identified in the operations section, and there may be other flood types that could be identified. At the earliest opportunity, a detailed analysis of records held by insurance companies would be the first step towards a generic flood-risk management policy.

Appendix D

Recommendations for further work

Investigations and analyses performed on the drivers of flooding highlight areas of inadequate knowledge and limitations in modelling capabilities that could usefully be addressed through further work to improve our ability to predict future changes in flood risk and reduce the currently high level of uncertainty surrounding those predictions.

This appendix presents recommendations for further work to address key issues and knowledge gaps concerning drivers of change in the risk of flooding and coastal erosion, strategic risk assessment, and evaluating the environmental dimension of flood risk. Recommendations have been prioritised, based directly on the evidence gathered and practical insights gained during Phase 2 investigations.

Although the further work recommended here has been disaggregated into specific topics to allow evidence-based prioritisation, the stakeholder and steering groups stressed repeatedly that further detailed work in the social, economic, physical and engineering sciences should continue within the framework of the holistic and integrated approach adopted in this Foresight project. If developed appropriately, the technique employed here could be used as a test bed to investigate the flood-risk implications of new knowledge and understanding of the drivers. Such development should, throughout, involve end-users and stakeholders. This is essential to ensure that research findings are both actively disseminated and relevant to the needs of policy- and decision-makers.

D1 Drivers of future flood risk

Catchment and coastal drivers

In setting priorities for further work and future research in the study of catchment and coastal drivers, the national scores for flood-risk impact and uncertainty analysis were used to identify drivers possessing both a high (increase or decrease) flood-risk impact and great uncertainty. For these drivers, further research into their nature and operation should enable reductions in uncertainty concerning climatic, socioeconomic, behavioural and environmental changes that have real significance in affecting future flood risk.

Research needs for drivers were prioritised using a research priority factor defined by:

$$RPF = FRI \times UBW$$

where, RPF = research priority factor, FRI = mean flood-risk impact score and UBW = mean uncertainty band width. The mean flood-risk impact score and mean uncertainty band width for each driver 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 significantly, and could be calculated if required). On this basis, the top 10 (out of 19) drivers deserving priority for further research are listed in Table D1 (note: the two drivers that operate indirectly were included in this exercise and as two drivers tied for tenth place, both are listed). The table also indicates the academic discipline(s) within which the research and development work would reside.

Table D1 **Priorities for further work to reduce uncertainty catchment and coastal drivers**		
Priority	**Driver**	**Disciplinary area**
1	Public Attitudes and Expectations	Humantities and Social Sciences
2	Stakeholder Behaviour	Social Sciences
3	Science Technology	Engineering, Physical and Biotechnical Sciences
4	Surges	Natural Environment, Engineering and Physical Sciences
5	Precipitation	Natural Environment
6	Waves	Natural Environment Engineering and Physical Sciences
7	Relative Sea-Level Rise	Natural Environment
8	Coastal Morphology and Sediment Supply	Natural Environment, Engineering and Physical Sciences
9	Social Impacts	Social Sciences and Public Health Medicine
10	Infrastructure Impacts	Engineering, Economic and and Physical Sciences
	Buildings and Contents	

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

Table D1 Indicates the drivers prioritised for research, but does not list particular topics or operational issues requiring further research. These details may be found in Appendix A, as part of the summary descriptions of the drivers.

Drivers of flooding outside the Indicative Floodplain (IFP)

Investigations performed during driver assessment revealed a variety of causes of flooding outside the indicative floodplain and large discrepancies in estimates of the associated risk. Much more work needs to be done to clarify the extent, causes and impacts of 'disconnected' flooding, particularly with respect to:

Priority 1: Muddy floods caused by overland flow in rural areas (especially field and drainage-ditch runoff) that enter houses and infrastructure directly.

Priority 2: Groundwater flooding in permeable catchments with fluctuating water tables, which leads to low-magnitude, long-duration waterlogging and surface flooding events.

Priority 3: Overwhelming of channel capacity or infrastructure failure along non-main river water courses that do not have floodplains.

Intra-urban drivers

The same approach as for catchment and coastal drivers was used to identify and prioritise further work on intra-urban drivers of flood risk. On this basis, the top ten drivers deserving priority for further research are listed in Table D2.

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

Priority	Driver	Disciplinary Area
1	Precipitation	Natural Environment
2	Public Attitudes and Expectations	Humanities and Social Sciences
3	Stakeholder Behaviour	Social Sciences
4	Regulation (influencing pathways)	Social Sciences
5	Science Technology	Engineering, Physical and Biotechnical Sciences
6	Social Impacts	Social Sciences and Public Health Medicine
7	Infrastructure Impacts	Engineering and Physical Sciences
8	Surges	Natural Environment, Engineering and Physical Sciences
9	Relative Sea-Level Rise	Natural Environment
10	Urbanisation	Engineering, Environmental and Social Sciences

Eight of the ten drivers in Table D2 also feature in Table D1. This is unsurprising given the considerable overlap between the causes of flood-risk changes at the catchment, coastal and intra-urban scales. Conversely, the fact that Surges and Relative Sea Level rise feature in Table D2 may surprise some people. It results, first, from dependence of drainage infrastructure in coastal settlements on being able to discharge freely to the sea and, second, great uncertainty regarding the joint probability of coincident flooding (simultaneous extreme pluvial and coastal floods) in towns and cities situated on the coast or along estuaries.

However, there are also notable differences. Elevation of the Precipitation driver to be the first priority in Table D2 stems primarily from the fact that current uncertainty in predicting the effect of climate change on the localised, short-duration, high-intensity events responsible for most intra-urban flooding is much greater than that for the larger, longer and less-intense precipitation events that generate flooding at the catchment scale. Uncertainty is compounded by lack of understanding of how, where, and to what extent additional runoff generated by uplift in short-duration, high-intensity storms will overwhelm complex urban drainage infrastructure to increase intra-urban flood risk.

Two drivers, Regulation (influencing pathways) and Urbanisation, appear in Table D2 but not in Table D1. The importance attached to these drivers follows from the fact urban landscapes are dominated by built environments in socially-constructed spaces. Hence, regulations that govern building and urban planning are important drivers, but ones that are clouded in uncertainty. This is especially so in scenarios that feature considerable Urbanisation, as uncertainty in Regulation (which may either increase or decrease intra-urban flood risk) is amplified by expansion of the urban area.

D2 Drivers of coastal erosion

Overview

Clearly, improved predictions of the forcing conditions imposed by relative sea level, waves and surges are a pre-requisite for improved predictions of coastal erosion. Hence, the recommendations for coastal erosion start by reinforcing those made earlier in the section dealing with coastal flood risk drivers.

Priority 1: Predicting shoreline changes

The study of coastal erosion in this project involved broad-based assumptions that were essential to produce general predictions at the national scale. While these predictions are valid, coastal areas respond uniquely to changes in coastal processes, depending on the local combination of forcing conditions, natural features, coastal defences and the state of morphological evolution of the particular system. This is recognised in all present shoreline planning studies. To increase the reliability and applicability of the predictions to specific coastal locations or situations, further work should be undertaken to ascertain the characteristic types, patterns and intensities of coastal erosion and shoreline change produced under the four scenarios.

- Research in engineering-geomorphology is needed to develop improved predictive models of beach profile and shoreline response to changes in relative sea level, wave energy and surge activity. Improved modelling capability would benefit not only the prediction of coastal flooding and erosion risks, but the evaluation of defence responses that might be adopted as well.

Priority 2: Socioeconomic information and assessments

Enhanced understanding of forcing conditions, physical processes and the extent of coastal erosion will only lead to improved decision-making in coastal management if they are matched by accurate analyses and predictions of the true social and economic implications for particular stretches of the coastline. Socioeconomic assessments require detailed demographic maps and sociological information, inventories of assets, installations, and infrastructure at risk and sophisticated analytical techniques to capture the health (psychological and physical problems) and social, as well economic, impacts of coastal erosion. Acquiring this information for sites at risk from coastal erosion requires studies at a much higher resolution than previously undertaken.

- Improved databases and further research on the human impacts of coastal erosion are urgently required to support enhanced assessment of the socioeconomic impacts of coastal erosion.

Priority 3: Vulnerability of coastal defences

Under the scenarios that are weaker economically it is unlikely that existing coastal defences could be maintained. Where defences are abandoned or allowed to fail there could be a rapid coastal response, as the coast retreats to a position commensurate with the forcing conditions – even without consideration of the impacts of climate change. In fact, under all four scenarios, the coastline will become *increasingly* out of balance with the coastal forcing, driving 'coastal squeeze' through landward retreat of the low-water position in response to sea-level rise, while the high-water position is constrained by defences. The result, foreshore steepening, will increase the exposure of existing defences and possibly accelerate their failure or abandonment.

- Further research is needed to investigate how the beach and shoreline profiles in front of existing defences will respond to climate change (that is changes in the *Relative Sea-level Rise*, Waves and Surges drivers) coupled with on-going 'coastal squeeze'.

- Foreshore steepening and scour in front of coastal defences are the most frequent reasons for infrastructure failure. Research should be performed to establish how serious and widespread failures of coastal defence infrastructure are likely to be under each scenario in the 2050s and 2080s.

D3 Strategic assessment of future flood risk in the UK

At present the Risk Assessment for Strategic Planning (RASP) analysis is restricted to England and Wales.

Priority 1: Extension of RASP analysis to Scotland and Northern Ireland

- A nationwide RASP capability is needed to provide the basis for a comprehensive assessment of flood risk throughout the United Kingdom and enable regional pictures to be compared and contrasted with confidence.

Priority 2: Enhanced database of flood-defence assets

Management and organisation of data within detailed, geo-referenced and frequently updated databases is now a key feature of all industries with proactive and targeted policies on asset management. However, data on flood and coastal defence infrastructure available for input to RASP modelling are limited to the location and type of defence. Also, the quantitative research performed in this project has revealed inconsistencies within the presently available databases. Improved forecasting of flood-risk changes and reductions in uncertainty can only be achieved if the quality of existing data is enhanced and coverage is expanded to include improved spatial referencing, geometric information (including crest heights for raised defences) and structure condition.

- Further work is required to improve the accuracy and coverage of existing databases of flood and coastal defence infrastructure.

Priority 3: Performance of defences during flood events

The validity of maps of future flood risk based on RASP analysis depends on accurate predictions of flood-defence asset performance in a future featuring non-stationary environmental conditions. There is, however, uncertainty concerning future levels of damage to, and maintenance of, flood- and coastal-defence infrastructure under different socioeconomic and climate-change scenarios. Research on the vulnerability of coastal-defence assets has already been proposed and similar research on inland flood defences is recommended here. A sustained period of monitoring would, in time, support the analysis of temporal trends of asset performance and allow development and verification of reliable predictive tools for possible defence infrastructure deterioration under different future scenarios.

- Monitoring and post-project appraisal studies should be performed to collect hard evidence on the type and severity of damage occurring to flood and coastal defences when they are subjected to extreme events and increased environmental loadings.

Priority 4: Integrated flood modelling

In assessing future flood risks in the Foresight project, it has been necessary to split the quantitative analysis of risk, using separate approaches and tools for pluvial, sewer, fluvial and coastal floods, but joint analysis of the performance of surface and sub-surface flood-defence and drainage infrastructure. In Phase 3, possible responses to the increases in flood risk predicted in this phase have had to be analysed through superposition of the predicted changes in risk for the different types of flood. This is less than optimal in terms of making accurate risk assessments, managing uncertainty and recognising that the capability of an integrated package of measures may be greater than the sum of its parts.

- To support accurate analysis of an integrated bundle of responses designed to improve flood management, the underpinning analysis tools must also be integrated. Research is required to produce a coupled, surface-subsurface flood-prediction model, or 'whole-system model' that accounts for the coincident effects of pluvial, sewer, fluvial and coastal floodwaters.

Priority 5: Dynamic risk assessment model

Climatic and socioeconomic changes in the UK dictate that both the probability and consequences of flooding will be non-stationary for the remainder of this century. Within Foresight, quantitative analysis has focused on predicting future flood-risk changes for defined time slices centred on the 2050s and the 2080s. This approach can provide only 'snap-shots' of the future. In reality, drivers change constantly and concurrently to produce a continuous time series of flood risk. A 'snapshot' can represent driver changes and the resulting spatial distribution of risk at the specified time, but is effectively a frozen frame in a moving picture. Such an approach cannot simulate how drivers interact, or reproduce the complexities of driver flood-risk feedback. Yet, the qualitative studies and deep driver descriptions have highlighted the importance of both these traits of the flooding system.

- Further work is recommended to develop a RASP-type analysis methodology capable of analysing flood risk dynamically through time, without significant increase in model run-time. This would reduce uncertainty and provide a significantly improved capacity to predict how the flooding system may evolve over time.

D4 Environmental impacts of future flood risk

Investigation of the environmental dimension of future flood risks reveals multiple areas requiring further work. In prioritising them, two major themes emerge. First, improved understanding of future flood risks rest on our ability to define accurately future environmental conditions, requiring additional modelling capability in climate change, geomorphology and ecology. Second, in order that the results of these models, expressed in terms of the environmental costs and benefits of changes in flood risk, can inform decision makers, it is essential that the way that the environment will be valued under different future scenarios is elucidated. To make progress within and between these major themes, four priority research topics are identified.

Priority 1: Broad-scale models of environmental impact

There is a particular need for analytical tools that can combine models from different domains. This is the case because accurate prediction of the environmental impacts of changes in flood probability and intensity rests on linking processes across environmental systems at the scale of the catchment or coastal cell. For example, prediction of the broad environmental outcome of an increase in floodplain inundation requires the capability not only to replicate the *functioning* of climatic, hydrodynamic, geomorphological and ecological systems, but also their *interactions*.

It is generally acknowledged that successful development of fully integrated environmental models is not immediately likely. A research aim that is achievable would be to produce a suite of matched models that can be linked or coupled within a spatially-referenced shell, such as a Geographical Information System. Key components of a linked modelling system that require further work at present are those dealing with geomorphological and ecosystem impacts at the broad scale required to inform decision- and policy-makers. Given the very high importance of the Stakeholder Behaviour and Public Attitudes and Expectations drivers, this is particularly important.

- Improved simulation and prediction of broad-scale environmental impacts requires models (coupled or, in the future, integrated) that account for processes, interactions and feedback loops within and between physical, chemical and biological elements of the environment. At present the analytical tools to undertake such simulations are far from perfect and further work is urgently required to address their limitations, especially in broad-scale geomorphological and ecosystem modelling of river and estuarine/coastal environments.

Priority 2: Environmental data

Lack of data constrains our understanding and ability to model the environmental dimension of flood risk. Without baseline data on morphologies, habitats and ecosystems – and the potential dynamic changes in those ecosystems in response to new influences – models cannot predict with any certainty the outcome of changes in flooding regimes associated with the impacts of particular drivers.

A co-ordinated and sustained data-assimilation campaign is required, encompassing morphological, habitat and ecosystem monitoring and data collation. This should be designed specifically to support the development of improved modelling and prediction tools for future responses to the changes in flood frequency, magnitude and duration.

- Field sites should be selected to create a suite of long-term monitoring studies, targeting vulnerable habitats at greatest risk from changes in flooding and coastal erosion, such as coastal grazing marshes, and valuable habitats with the greatest potential to benefit from changes in flood risk, such as washlands and wetlands.

Priority 3: Accounting for uncertainty

The models developed under Priority 1 and the data collected to support their application under Priority 2 will be subject to uncertainties associated with:

- Measurement.
- Sampling.
- Assumptions and simplifications in the algorithms and analytical tools.
- Error amplification within and between models.

- Errors in the assumed basis for links between models.

- Stochastic errors.

Further work is required to resolve issues concerning uncertainty-handling in the construction of composite risk models of flooding systems, including issues of model choice in view of model scale, complexity, credibility and cascading uncertainties through coupled model components.

- Implicit consideration of uncertainty within models of the environmental dimension of flood risk is essential, but further research is necessary to make uncertainty analysis a routine aspect of environmental modelling, so that stakeholders can be provided with information on uncertainties in model predictions in a standard and readily understandable format.

Priority 4: Valuing the environment

The value of the environment as a resource, and therefore the costs and benefits of its responses to changes in flood risk, must be translated into human welfare effects to provide the relevant information to stakeholders. While current knowledge on ecosystem values is fairly advanced, attempts to use economic values more routinely through benefits transfer have so far been inconclusive and further original valuation studies are necessary.

The challenge to improving environmental-impact predictions specific to the context of climate and socioeconomic change is even greater. Introduction of future scenarios complicates benefit-transfer calculations because environmental values vary across scenarios. Differences relate mainly to preferences, income levels, income distribution and institutional structures in each of the scenarios, all of which will influence the relative values of environmental impacts.

- Further research into understanding environmental values and how current environmental preferences are formed is urgently required as a starting point in developing robust mechanisms for valuing the environment and to inform the debate on how the environmental dimension of flood risk will change under different climatic and socioeconomic futures.