ADAPTABLE URBAN DRAINAGE - ADDRESSING CHANGE IN INTENSITY, OCCURRENCE AND UNCERTAINTY OF STORMWATER (AUDACIOUS)

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1. Introduction

There is now considerable interest in flooding, climate change and how best to manage these, not only in the UK but worldwide. A number of initiatives are underway in the UK under the general perspective of adapting to future changes and the seemingly increasing occurrences of flooding that prompted and have followed the Foresight Future Flooding project (Evans et al, 2004). This has led to the 'Making Space for Water' (Defra, 2006) initiative that is now encouraging the development of a new approach to 'integrated urban drainage' (IUD) in England and Wales. Prior to this in 2003, a portfolio of projects was initiated under the Building Knowledge for a Changing Climate (BKCC) programme, funded primarily by EPSRC and UKCIP. There are now 9 BKCC projects (BKCC, 2006) of which there are 3 that are generic and one specifically relevant to flood risk management. The generic projects address: climate change and rainfall prediction (BETWIXT); economic and social information for future scenarios (BESEECH) and new impact and uncertainty methods addressing climate change risk assessment (CRANIUM). AUDACIOUS deals with changing flood risk due to rainfall and accounting for climate change in relation to existing drainage systems in small urban areas. A further project, ASSCUE is also of relevance as it deals with 'Adaptation Strategies for Climate Change in the Urban Environment', i.e. urban land use, form and layout.

Since AUDACIOUS began in 2003, the Flood Risk Management Research Consortium (FRMRC) has also been established with funding from EPSRC, the EA, water industry and others to take a broader perspective on flood risk management encompassing the whole system (FRMRC, 2006). FRMRC is not concerned, however, with buildings and flood resilience.

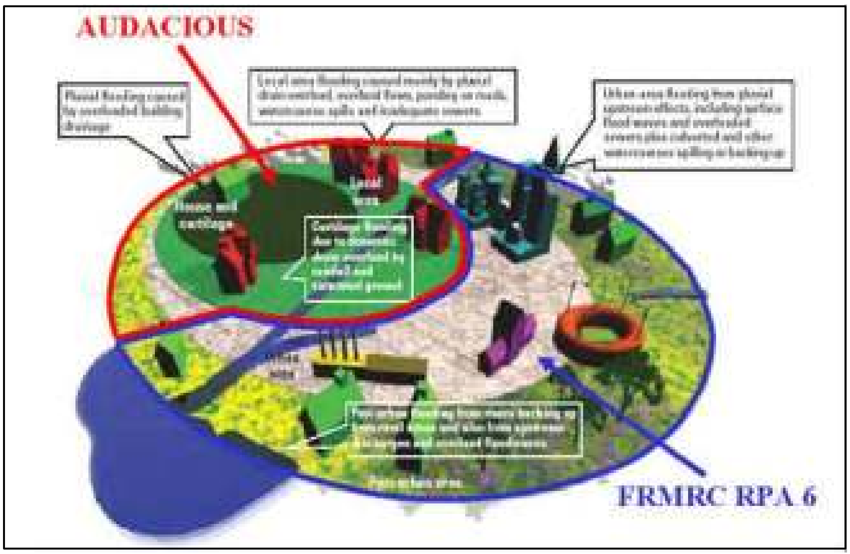


Figure 1 spatial scales and aspects of urban flood risk dealt with in AUDACIOUS

AUDACIOUS deals with the urban drainage system up to the connection into the public sewerage system (Figure 1), although it does consider the potential downstream impacts and interactions within the wider drainage network. In addition to the academic partners and CEH, the following organisations have contributed to the AUDACIOUS project by funding, steering group membership, case studies or otherwise:

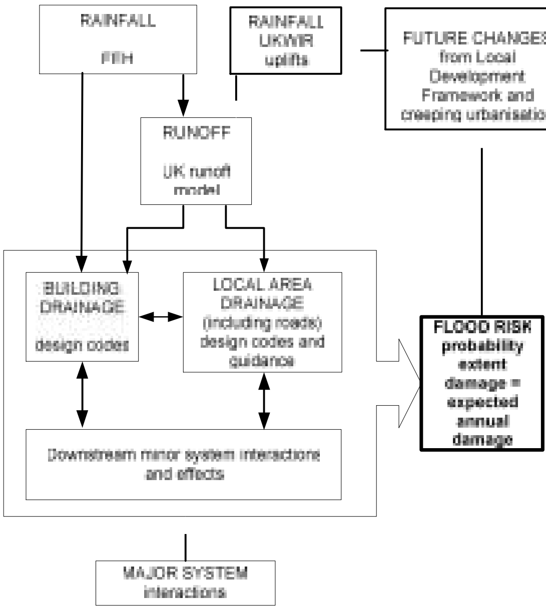
- Scottish Water
- MWH
- Association of British Insurers
- Environment Agency
- Yorkshire Water
- CIRIA
- Micro Drainage Ltd
- Bradford MBC
- Thames Water
- Fullflow Ltd

- UKWIR
- HR Wallingford

Their support, input and engagement has been essential. The project team would also like to acknowledge the funding from EPSRC and BKCC and the importance of the integrating framework across all of the BKCC projects.

2. Objectives and outputs

AUDACIOUS set out to address the non-main drainage aspects of local area flood risk management. The aim has been to investigate key aspects of the effects of climate change on existing drainage in urban areas and provide tools for drainage managers and operators to adapt to uncertain future scenarios. This plugged a gap at the time in drainage related research, in that it set out to establish a rational framework for problem-oriented, cost-efficient, adaptable and sustainable decision-making for those owning and responsible for managing, operating, regulating and developing urban drainage systems at the local level in order to mitigate likely current and potential future problems arising as a result of climate change. The flood risks were those arising from direct rainfall on to urban areas and the overloading of existing drainage networks of the type experienced in Market Weighton and in some areas of London in the 'wettest drought in history' in June 2006.



- To provide new procedures, computer models, and appropriate (targetted to particular users) guidance (toolbox) to facilitate the assessment of climate change impacts and the development of mitigating responses for building and local drainage systems.
- To enable and demonstrate the integration of the models and procedures with the behaviour of, and within, the wider context of drainage and urban systems.
- To establish the baseline procedures for evaluation and mitigation of the effects of climate change on existing urban drainage and to disseminate these widely.

Overall AUDACIOUS is intended to help build capacity to cope with future uncertainty in relation to the management of local area drainage flood risk.

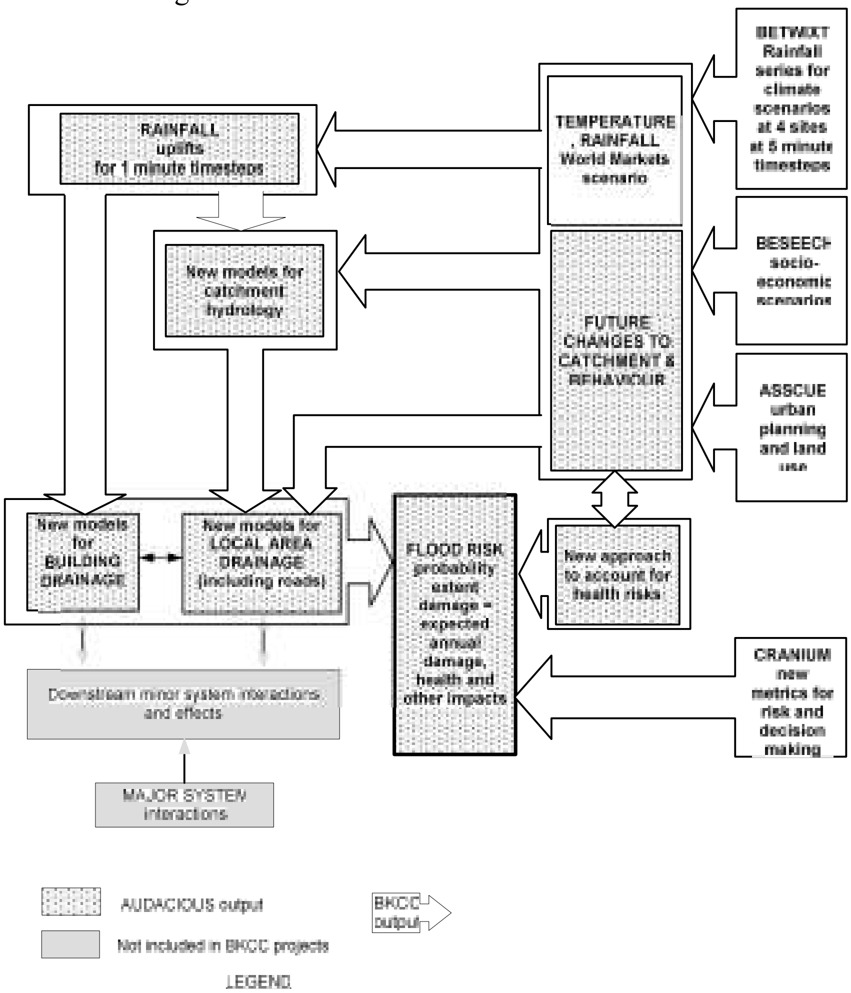


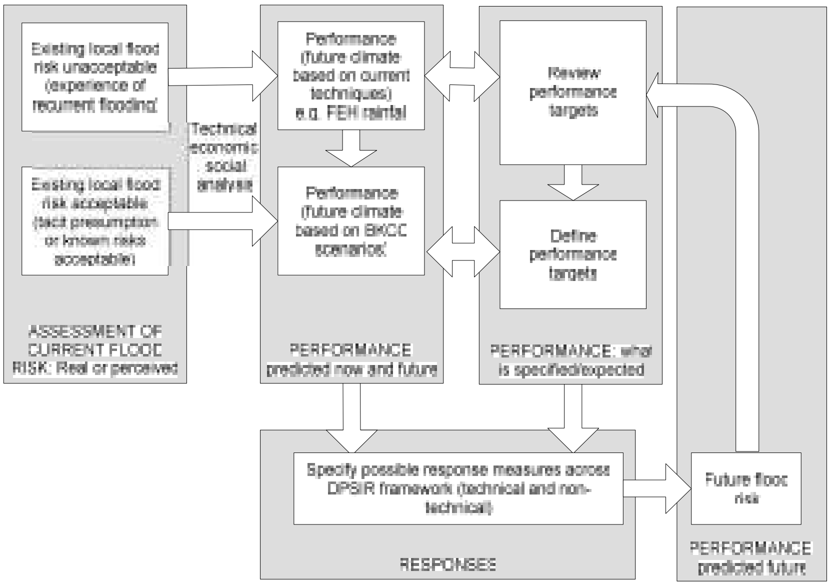
Figure 3 BKCC and AUDACIOUS – estimation of future flood risk due to climate change

The outputs from the project comprise:

- A handbook that is intended to be flexible and adaptable as knowledge advances and is in a format suitable for access by non-specialists
- A technical report that provides the detail behind the handbook
- A number of case studies to demonstrate the use and application of the handbook.

3. AUDACIOUS Constituent parts

The differences in analysis of local area drainage flood risk brought about by the BKCC programme and AUDACIOUS are illustrated in Figure 3 and may be compared with Figure 2. The assessment of risk can then be linked to responses using a logical framework, as in Figure 4. The responses considered can be set within a Drivers-Pressures-State-Impact-Response (DPSIR) framework (e.g. Ashley et al, 2006), where responses can be effected at any stage, i.e. anywhere in Figure 3, although AUDACIOUS has not explicitly considered responses that may influence climate (and rainfall).


Existing local flood risk unacceptable (experience of recurrent flooding)
Existing local flood risk acceptable (tacit presumption or known risks acceptable)
Technical economic social analysis
ASSESSMENT OF CURRENT FLOOD RISK: Real or perceived
Performance (future climate based on current techniques) e.g. FEH rainfall
Performance (future climate based on UKCC scenarios)
PERFORMANCE predicted now and future
Review performance targets
Define performance targets
PERFORMANCE: what is specified/expected
Specify possible response measures across DPSIR framework (technical and non-technical)
RESPONSES
Future flood risk
PERFORMANCE predicted future

Class	Stakeholder group	Media format
A Property users	Householders Community groups Property owners Commerce Industry Public services	Primarily paper based with community support. Also web based information.
B Property managers	Facilities managers Property surveyors Developers Insurers/mortgage providers	As above, but access to simple tools – spreadsheet or database formats
C Government and agents	Local Authorities Highways Agency Network Rail Environment Agency Sewerage undertakers Specialist Consultants, including land management and conservation Government departments	As above plus access to fully operational tools in various formats

Table 1 key potential stakeholders in AUDACIOUS

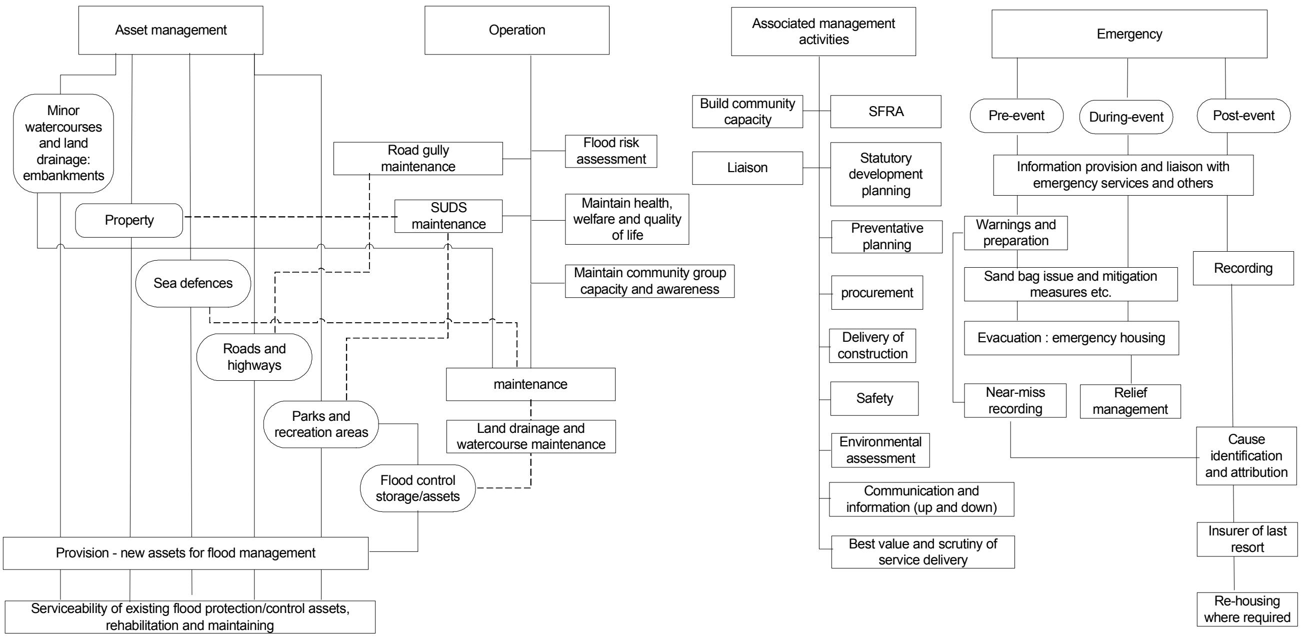


Figure 5 Part of the ontology for flood risk management for Local Authorities

3.2 Defining problems - and adapting

There are two types of problem within the aegis of AUDACIOUS:

1. Where there is evidence of unacceptable flood risk – because flooding has occurred
2. Where there has not been any flooding recently but future climate change effects may increase the probability of flooding.

There are major difficulties in defining what is or is not acceptable flood risk. This is particularly difficult in relation to local pluvial events. Whilst it is well defined for main drainage (e.g. DG5 register) it is less clear for other aspects of the drainage system.

Design (performance) standards for local and building drainage should generally comply with BS EN752, the Interim Code of Practice for SUDS or possibly EN12056. These standards range from 2 year storm events up to potentially 100 years. The main drainage network is designed and operated to provide various standards of protection, depending on the sewerage local undertaker, although these would usually comply with 'Sewers for Adoption'. The current difficulties of integrating these various standards, even in current climatic contexts have already been outlined (Blanksby, et al, 2005; Defra, 2006) and are being addressed in the Defra follow-on projects and the FRMRC. Nonetheless there are few projects dealing with local and building drainage issues. Most building related work continues to be interested in flood proofing or making buildings flood resilient. AUDACIOUS has taken a more holistic view encompassing the local area drainage (Figure 1) and bringing together each of the key components required to firstly assess risk now, in the future and also how to respond and manage these risks.

Access to codes of practice and standards gives specific design criteria for performance, such as storm return period, which differ for the various vulnerable components in the urban area (Blanksby et al, 2005). Until recently, the baseline rainfall intensity for building drainage was suggested as 75mm/h where some ponding was acceptable. More recently extreme value statistical approaches have been recommended. In (BS) EN12056 Part 3: 2000 runoff is determined using the rational formula; with rainfall intensity selected using local rainfall statistics, otherwise selected regionally. In the Appendix for the UK, EN12056 gives four categories for estimating design rainfall. The rainfall may be determined by reference to Meteorological Office maps provided in the standard. This includes the use of 'probable maximum rainfall', a dubious concept given the variability in spatial and temporal behaviour of rainfall (e.g. Marshall, 2003). When climate change uncertainty is introduced it makes this concept even more elusive.

Local area drainage management is currently very complicated due to the shared responsibilities. Private property and landowners have certain duties not to cause problems to others, Local Authorities may also have responsibilities for some watercourses or permissive powers to act and certainly have emergency responsibilities under Civil Contingencies legislation. In addition the major watercourses and increasingly, the more important minor ones, are under the control of the EA. The roles and duties of the main stakeholders are set out in the recent Making Space for Water review (Defra, 2006); although this (ironically) largely ignores the place of the householder or local land owner.

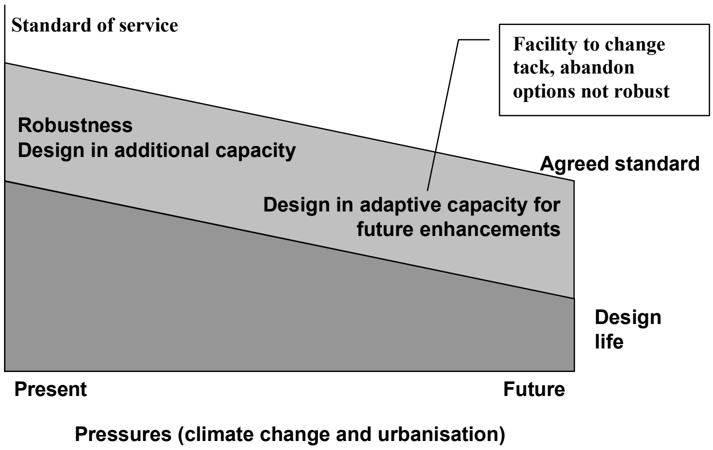


Figure 6 Adding robustness and adaptive capacity

Designing new urban drainage systems for exceedance has been the subject of a recent CIRIA report (Balmforth et al, 2006). In this, there are categories of 'Exceedance Flood Risk Assessment' (EFRA). Level 1 corresponds to 'simple small areas' and is applicable to property flooding rather than health and safety risks. For these level areas, analysis initially uses the rational method to determine a critical time of concentration which is assumed to be the critical storm duration. Then it is recommended to use 30 or 100 year return period events to assess whether or not flooding will occur. Once it is found that the drainage system cannot cope, the severity of flooding (depth, velocity) is determined. Together the consequences and probability of flooding provide the 'risk score'. Ultimately the components of risk can be used in a matrix to define when risk is 'high' or unacceptable. This will depend on local circumstances. CIRIA C635 then provides methods for identifying flood exceedance pathways and how to manage these and storage systems for existing and new development areas.

The framework set out in CIRIAC635 conforms with the AUDACIOUS project outputs and provides some important details as to how to assess local characteristics such as roads as pathways for exceedance flows. AUDACIOUS provides more explicit guidance for the inclusion of climate change effects into the analysis. Figure 6 illustrates the overall approach taken in AUDACIOUS, where over time, there will be a need to ensure that flood risk measures are able to adapt as knowledge and experience in relation to climate change advances. The agreed standards (performance) may decline for different parts of drainage systems, with householders for example, having to deal individually with their own risk management.

The overall AUDACIOUS approach for typical Local Authority use is shown in Figure 7 for known property flooding problems. There is an equivalent process for where flooding has not so far occurred but may be a risk in the future. The following sections introduce the new approaches developed in AUDACIOUS to the various components in local area flood risk assessment (Figure 3).

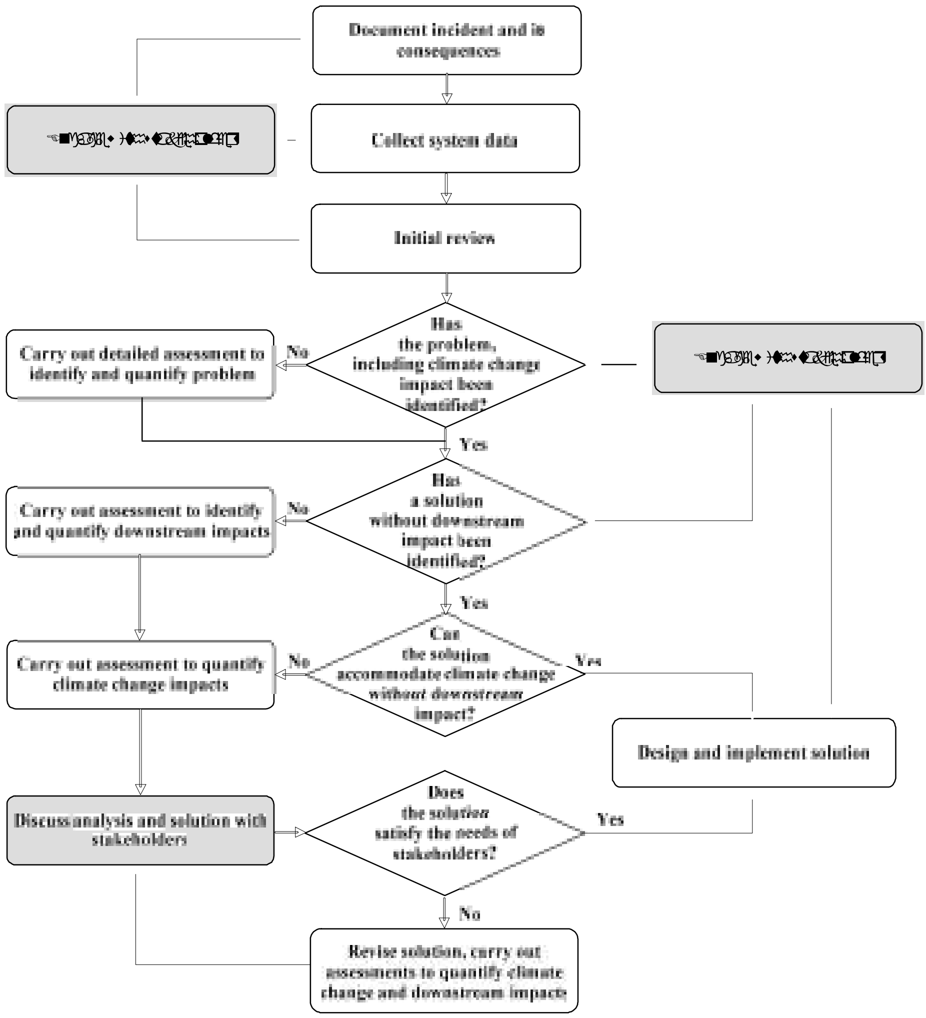


Figure 7 Investigation process for current flooding problems

3.3 Climate and Rainfall

Climate and rainfall is at the core of the BKCC programme and a specific project, Built Environment: Weather Scenarios for Investigation of Impacts and Extremes (BETWIXT) set out to provide integrated outputs for rainfall, temperature, wind speed, evapotranspiration and other parameters based on the UKCIP 02 predictions for four emissions scenarios (high, medium-high, medium-low and low). The linkages between rainfall and the other parameters are made at daily scale, but rainfall is further disaggregated to hourly and five minute intensities. The outputs of BETWIXT are given in the form of a time series from which further analysis may be made.

A rainfall generator (RainSim) produces long series rainfall at seventeen locations throughout the country (Figure 8). The choice of the locations was based on the availability of long series weather records, upon which the analysis behind the series was based. Given the outputs from BETWIXT, AUDACIOUS set out to develop methods by which the rainfall may be adapted for use at a local scale.

Figure 8: Location of RainSim outputs

The first stage of the process was to carry out an assessment of the RainSim outputs and to compare them with the TSRsim generator developed in the UKWIR project and to benchmark them against observed data (Kellagher 2005). The study which used data from the sites at Elmdon and Ringway concluded that based on the limited data available, both tools are useable in assessing drainage system performance for all aspects of sewerage particularly for critical durations between 1 to 6 hours, but that below this duration both models tend to produce events that do not accurately reflect the observed data. Even so, there were some notable differences in the outputs and the work highlighted the uncertainty in predicting future rainfall.

Following this, a more detailed analysis of the outputs of four sites was made. The objective of the study into the frequency, depth and duration of the five minute outputs for the different emissions scenarios was to determine uplifts which could be applied to current synthetic rainfall for design purposes. Although it is recognized that there is a need to produce time series rainfall for sewerage undertakers, the immediate needs for conveyance in local drainage is for synthetic design events with five minute time intervals, and issues relating to storage may be dealt with using longer time steps.

The study revealed that there was a considerable variation in the uplifts between sites, emissions scenarios, the epochs for which the outputs were produced, the duration and return period of the event and seasons. In some cases, particularly in summer, the uplifts were less than one, but in winter they were as high as 1.4. It was concluded from both studies that seasonal changes will be significant and that there is a need for further work to develop rainfall futures at local scale. It was also concluded that the degree of uncertainty in rainfall prediction made an adaptable approach to flood risk management essential. In order to utilize the RainSim outputs it will be necessary to identify the uplifts for each of the 17 locations (Figure 8) and then to make adjustments to produce suitable uplifts at a required location. However, the Environment Agency has recently sponsored the development of a tool to produce rainfall series at a horizontal resolution of 5 km^2 (Kilsby et al, 2006). Although the current tool called Environment Agency Rainfall and Weather Impacts Generator (Earwig) currently only delivers daily rainfall totals it has the potential to be modified to produce higher resolution outputs and may well prove to be a key output resource for the future prediction of rainfall.

Currently, however, it is apparent that warmer wetter winters will lead to more waterlogged ground and less precipitation falling as snow; hotter drier summers will lead to reduced soil moisture, and less frequent rainfall, but rainfall intensity may increase and seasonal patterns will change in autumn and springtime, with increased intensities which may coincide with increased depths on waterlogged ground. It is recommended that for the foreseeable future, the PPG/PPS25 approach be used. In view of the uncertainties in rainfall estimation, the initial case studies for AUDACIOUS initial uplifts of between 10% and 40% have been used.

3.4 Hydrology

Although urban runoff is usually mainly the product of rainfall over the impervious area (and thus allow climate change impacts to be predicted largely from changes in rainfall intensity alone), the effect of pervious areas and soil conditions can be considerable, due both to the ‘runoff’ they generate and their influence on losses (through surface cracks or otherwise) away from impervious surfaces. Runoff will also be influenced by the flora which may change in future due to the whole range of climatic differences from present day.

In analysing urban runoff data to develop the Wallingford Procedure PR equation, the importance of both soil type and antecedent conditions was clearly identified. The work also showed that a contributing pervious area that varied with mean soil moisture corresponded more closely with observations than an excess of rainfall intensity over a pervious area infiltration rate. This may be due to the large spatial variability of surface properties, but also to the dependence of any derived critical infiltration rate on the model time step. The varying percentage runoff approach was more robust.

Impervious surfaces respond most to intense summer rainfall, occurring when pervious areas are dry and absorb much of the rainfall and so give little 'runoff'. Lower intensity winter rainfall may produce less impervious runoff, but wetter soil conditions lead to greater pervious runoff. A fuller understanding of climate change impacts on the combined response of impervious and pervious area runoff is thus required. This is especially important given the increasing pressure to reduce urban runoff and pollutant washoff by use of SuDS that comprise a range of 'pervious' surface infiltration and storage methods.

The last concerted attempt in the UK to improved urban runoff modelling resulted in the 'New runoff' or 'NAPI' model giving percentage runoff (PRt) at timestep t as:

$$PR_t = IF*PIMP + (100-IF*PIMP)*NAPI_t/PF \qquad (1)$$

where IF = imperviousness condition of 'paved/roof' area
PIMP = percentage of paved/roof area in catchment
PF = notional maximum soil moisture depth (S_{max}, fixed at 200mm)
and $NAPI_t = k^{dt/2}\, P_{dt} + k^{dt}.NAPI5_{t-dt}$ (with time step dt in days)

NAPI is an antecedent precipitation index based on rainfall P_t less available depression storage. Actual depression storage is reduced by daily potential evapotranspiration E_t estimated from mean monthly data for the relevant Met Office (MORECS) grid square. The factor k is set by Flood Studies Report SOIL types 1 to 4.

Equation (1) uses $NAPI_t$ as an indicator of current soil moisture status m_t, and sets the pervious area runoff factor to m_t/S_{max}. Soil moisture is modelled more explicitly as the balance between rates of infiltration, *f*, soil drainage, *d*, and evaporation, *e*, by the following equation:

$$dm/dt = f - d - e \qquad (2)$$

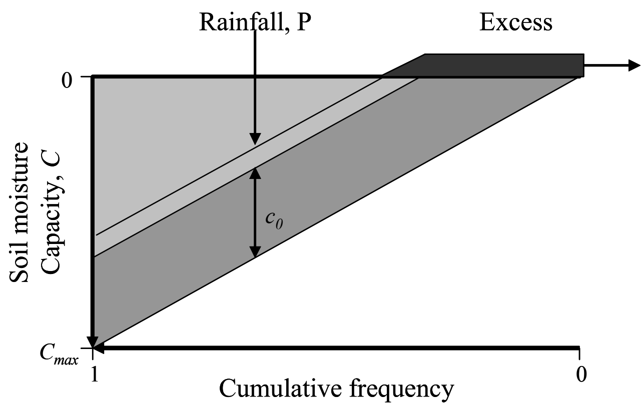


Figure 9 Soil Moisture capacity distribution

This approach was tested, with *f* taken as rainfall *i* less runoff $i(m_t/S_{max})$, and drainage and evaporation attenuated by m_t/S_{max}. However, the model was difficult to calibrate and could not be properly developed in the time available. The NAPI model (1) worked well enough with the available calibration data, but does little to allow higher soil moisture in winter (other than make smaller depression storage adjustments to P_t due to lower winter evapotranspiration), and nothing to stop m_t exceeding S_{max} (resulting in more runoff than rainfall). Hence it has limitations, particularly under winter conditions.

Since testing the original soil moisture model (2), a number of improvements have been made. Firstly two commonly used conceptual parameters have been implemented: 'field capacity' *FC* allows drainage (at a rate of $d=k(m_t\text{-}FC)$) only if m_t exceeds *FC*; and 'rooting depth *RD* attenuates evaporation to $e=Et(m_t/RD)$ only when m_t drops below *RD*. Secondly, a linear Probability Distributed Model (PDM) has been applied in which soil moisture capacity is assumed to vary uniformly across the catchment from zero to a maximum of C_{max}. The resulting moisture capacity distribution is presented as a triangle in Figure 9.

Previous rainfall history is assumed to have filled all the soil area with capacity less than c_0, creating a wet proportion of the catchment that produces runoff, equivalent to a runoff factor of c_0/C_{max}. Noting that average soil moisture capacity is $0.5C_{max}$, and that mean moisture content m_0 can be found by considering the relative areas of the shaded triangles, it can be shown that the instantaneous proportions of rainfall going to runoff and infiltration, and an updated value of c_0 for the next timestep are given respectively by:

$$c_0/C_{max} = 1 - (1 - m_0/Smax)^{0.5} \quad (3)$$

$$(1-c_0/C_{max}) = (1 - m_0/Smax)^{0.5}, \qquad [\text{infiltration rate } f=i(1-c_0/C_{max})] \quad (4)$$

and $$c_1 = c_0 + P \quad (5)$$

The linear PDM model has a reasonable conceptual basis, and has been found to give good overall fit to natural runoff rates. The approach has recently been implemented in the ReFH model that 'Revitalises' the Flood Estimation Handbook Hydrograph method (Kjeldsen et al, 2005). In this case, equation (2), with the above expressions for *f*, *d* and *e*, was solved numerically at a daily timestep to update soil moisture to the start of an event, and equations (3) and (5) were solved during a storm event. The model has four parameters to calibrate (S_{max}, *FC, RD* and drainage factor *k*), but given the limitations of the available data, fixed rules were adopted for three parameters (k = 0.8; RD= 0.3 FC; FC = fixed by long term simulation of daily mean flows), and just one parameter S_{max} was calibrated (as a factor on *FC*). Optimum S_{max} values were then related to soil type within the catchment. Note that unlike the NAPI model (1), it is S_{max} that was related to soil type rather than the drainage factor *k*. Note also that by ignoring evaporation and drainage during an event, the model has not yet been properly implemented for use in continuous simulation.

An extended version of the model has been developed for use in urban drainage applications to better suit urban catchments, and to allow continuous simulation. Firstly, the full version of the model (equation 2 with the relevant expressions for *f*, *d* and *e*) is being applied between events at a daily timestep, and during events at a suitable event timestep (currently 1 minute). Secondly, the existing NAPI depression storage model has been incorporated, together with the paved/roof area runoff factors IF from equation (1). The varying pervious area runoff factors derived by the PDM have thus effectively replaced the $NAPI_t$/PF factor of equation (1). The implementation is more clearly an upgrade from the existing NAPI model rather than a transfer of the ReFH model.

The model is still being assessed, and values for the model parameters have not yet been determined. In particular, although the depression storage model is thought to be worthwhile, it is likely to result in significantly different optimal values of S_{max} from those in ReFH, particularly when applied to the small pervious areas that occur within a developed area rather than to large undeveloped subcatchments. It is likely that separate models will need to be applied to such different types of area. It should also be noted that the ReFH version of the model made no attempt to define drainage rates for different soil types, which is an area where existing urban practice differs, and is worthy of further investigation.

3.5 Building drainage

An enhanced simulation model representing building roof drainage and local drainage has been developed (Wright et al, 2006), which incorporates the interaction between the various drainage components, as well as runoff from small-scale pervious and impervious surfaces. The (conventional and siphonic) roof drainage section of the model encompasses three 'modules' representing roof flow, gutter flow and pipe flow. The roof flow module calculates gutter water depths that, via flow from the impervious or 'green' roof surface, determine the flow rate feeding connected downpipes. The gutter flow module introduces a fundamental component of the overall modelling approach by incorporating a full dynamic solution of the equations representing unsteady open channel flow with lateral inflow. As downpipe flow may be annular with transition to full bore, the downpipe module also utilises a full dynamic solution, thus enabling the simulation of mixed flow regimes.

3.6 Local areas

Local areas, comprising the interfaces with building drainage, curtilages, local roads and other features have been partly modelled using hydrographs. The local drainage model represents resultant inflow from connected downpipes combined with flow from other system entry points (e.g. gullies). Although this model simply routes system flows and does not simulate more detailed flow dynamics such as the propagation of full bore flow, it nonetheless allows for flow interactions, as well as facilitating an assessment of flow capacity limits and system surcharge. Developing the models in this way allows applicability within the context of a more integrated approach to drainage design which comprises GIS represented flow pathways derived from LIDAR. It is possible to combine the various inputs to the local area based on the building drainage inputs and the modified hydrology model above, to assess the performance of a local drainage area and the passage of flow in and out. Ultimately this will be done using a new computer model of the interactions within the drainage areas and the minor drainage systems. This model is currently under development as part of the FRMRC programme at the University of Exeter.

3.7 Interactions

There are main drainage network interactions which are important when assessing the performance of local drainage systems. It is normally essential to at least consider whether or not there is a network model and the extent of the model. Typically drainage area plan models are not set up at a locally detailed level required to understand local area drainage performance; necessitating refinement of the DAP model. However, where there is a potential capacity problem due to overloading, the local area drainage may malfunction. Provided the main drainage provides industry standard levels of service this should not be a problem.

3.8 Cost-benefit-risk/health

As the analysis is dealing with future conditions it is essential to include here the outputs from BESEECH project, which define the local socio-economic conditions over time. BESEECH, however, dealt only with comparatively short timescales (up to 2025 and 2050). The four baseline scenarios used in the Foresight project (see Ashley et al, 2006 for application of these to sewerage) were also used in the BKCC projects. Projections for demographics, wealth and lifestyle have been made for the case study areas described in section 4. The case studies based in Yorkshire corresponded closely with the Regional Spatial Strategy up to 2025. It is worth noting that the Government's chief scientific advisor, Sir David King, recently indicated that the UK is on the trajectory that corresponds most closely with the World Markets (and at least in the short term, high-emissions) scenario.

AUDACIOUS uses the commonly adopted definition of risk which involves the probability of an event occurring and the consequences of the event (but see Gouldby & Samuels, 2005). At national and regional scale the assessment of risk can be a complex matter, requiring the identification of economic, social and environmental 'costs' or impacts. However, at local scale, the assessment is usually much simpler as the number of stakeholders involved is smaller.

For existing properties with quantifiable flood risk, property owners, users and other stakeholders such as insurers have to assess the situation in terms of the consequences of the individual event, (cost and other), and the frequency of the event. They then have to assess if they can live with the risk, or if it is beneficial for them to adapt to change the risk. It is conceivable that some businesses could live with a higher probability of flooding, providing that there is an economic gain, but the more commonly held expectation is that it is beneficial to invest in measures that will reduce the frequency or consequence of flooding.

In making these decisions, the stakeholders will wish for certainty in the assessment of future flood risk, but the reality is that certainty cannot be guaranteed and so strategies are required to help them make the best decision. This is the essence of the question behind Figure 6. Should there be investment to build in robustness, or adaptive capacity? How much investment is required, and when is it required? The answers to these questions depend on the nature of the flooding, the relationships between and the attitude to risk of the stakeholders. For instance, does a tenant need to insure contents against internal flooding from a gutter which is maintained by a landlord, or is it in the tenant's interest to contribute to increasing capacity and more frequent maintenance?

Whatever the circumstance, it has been possible to develop a simple procedure to help in decision taking.

- **Step 1: Understand and quantify the current flood risk and the desire and capacity to manage it.**
- **Step 2: Define the epochs for which future risk assessments will be made -** In BKCC these have been identified as the 2020s, 2050s and 2080s
- **Step 3: Understand the worst case scenario -** Using the rainfall scenario generating the highest uplift, and where appropriate other (socio economic drivers) identify and cost the adaptations required to produce an acceptable flood risk.
- **Step 4: Quantify the need for robustness, and/or the capacity to adapt** - This depends on the capacity and desire to make provision for future scenarios that may or may not happen and the capacity and desire to revisit the problem if the chosen course of action proves to be inadequate at some time in the future.

It is generally considered that uncertainty increases the further into the future that a projection is made. For instance the difference between the rainfall uplifts for the low and high emissions scenarios is small in the 2020s and the draft Spatial Strategies reflect World Markets policies enshrined in European policies and are highly likely to be relevant in the 2020s. In this case, and providing that there is potential to adapt as time progresses, it may make sense to develop a solution that will meet the worst case rainfall and world markets socio-economic scenarios in the 2020s, and, given better knowledge of potential climate change and socio-economic drivers in the 2050s, review the flood risk at the appropriate time. However, if the cost of managing the worst case scenario is no more or only marginally greater than the cost of managing the problem to the 2020s, the decision takers may decide to implement these forthwith.

The key conclusion is that there is no alternative to considering the need to be adaptive. The current degree of uncertainty is so great that optimisation is not an answer, although optimisation methods may be used to develop solutions to problems associated with specific scenarios.

While the devastation to properties is usually obvious following a flood event, the impacts on people (where drowning and serious injury does not occur) can be much more subtle. The health effects relating to flooding are generally split into those associated with the immediate event (with drowning being the most obvious) and those arising after the flood has resolved (i.e. post-onset, which may be related to exposure to flood waters, the clear-up process or stress and anxiety).

Health impacts can also be considered to be direct or indirect, with indirect impacts perhaps resulting from damage to infrastructure, food supply and so on. Indirect impacts are not considered explicitly in AUDACIOUS, except for flooded properties with private water supplies. Unfortunately the health impacts of flooding do not lend themselves to controlled prospective epidemiological studies, where those that are flooded are randomly allocated and matched to a control group, who do not experience flooding. Thus, much of the literature is based on opportunistic retrospective studies of flooding (sometimes conducted a considerable time after the event), case studies or anecdotal evidence. Literature based information on flooding and health was nonetheless used, with particular reference to studies which quantified the impact of flooding on health. Following a flood event, if the numbers of houses flooded, the flood depth and flood velocity and sociodemographics of the area are known it is possible to determine the health impacts. The main difference under climate change would appear to be the frequency of flooding - therefore health impacts/year automatically increase because people are being flooded (or fear the possibility) more often. Mental health impacts are in general the biggest health impact.

The aim of the health related flooding assessments is aimed at, where possible, the quantification of the *individual* health outcomes as Disability Adjusted Life Years (DALYs). These can then be summed in order to compare different events or remediation options. DALYs are summary measures of health that allow comparison of effects across a wide range of health outcomes, including both mortality and morbidity. The measure combines years of life lost by premature mortality (YLL), with years lived with a disability (YLD), standardised using severity or disability weights. The weights range from 0 (perfect health) to 1 (dead). The measure was derived to use in the ongoing Global Burden of Disease study which aims to compare DALYs resulting from various illness and environmental risk factors (such as unsafe sanitation) across global regions. It uses a standard life expectancy at birth of 80 years for men and 82.5 years for women, and DALYs are discounted at 3% and age weighted (Prüss and Havelaar, 2001). For the purposes of AUDACIOUS figures from the interim life tables for England of 76.2 for men and 80.72 for women – (rounded to 76 and 81) have been used (GAD, 2005), with no discounting or age weighting. Disability weights have been derived for a number of disease categories (WHO 2005b; Stouthard et al., 1997), where possible these have been used directly. Where severity weights have not been previously derived these have been extrapolated from similar illnesses.

The quantification of health impacts is based principally on:

- 'Flood risks to people' research project (DEFRA/EA 2004, 2005) for estimates of deaths and serious injuries; and
- WHO methodology, adapted from the comparative risk assessment calculations of global disease burden (Prüss et al., 2002), which combines incidence in the general population with relative risk values derived from the literature.

Research into the health effects associated with flooding and the number of health reviews conducted (e.g. Hajat et al., 2003; Tapsell and Tunstall, 2003; Ohl and Tapsell, 2000) seems to have increased relatively recently, perhaps driven by the increase in flooding seen during the twentieth century (Milly et al., 2002) and the forecast from climate change modelling that this trend will continue (Evans et al., 2004).

Health effects have been categorised into a number of groups:

- mortality and injuries;
- infection; and
- mental health effects.

In order to understand what DALY scores mean it is useful to have other examples of how DALYs have been used and how other day-to-day occurrences score. In the WHO guidelines for drinking water quality (WHO, 2004) it has been suggested that the tolerable disease burden from drinking water should be no more than 0.000001 DALYs per person per year.

3.9 Local decisions in the context of district drainage

Whilst AUDACIOUS is about local drainage, it has to be recognized that it is not always possible to make good decisions in isolation. For instance, it is not possible to assess the potential future risk of water flooding onto a property or to be sure that adaptive measures taken to manage flood risk within a property will not adversely affect downstream properties and artefacts without considering the performance of the drainage systems upstream and downstream of that property. The assessments, policies and guidance required to enable local decisions to be made will require collaborative working between local authorities, sewerage undertakers and drainage authorities, and is outside the scope of AUDACIOUS; being addressed in FRMRC and MSFW. However, the outputs are being designed to meet the needs of property owners and occupiers and to interface with the wider FRMRC activities.

3.10 Responses and Adaptation (behaviour and perceptions, capacity building)

As outlined above, there are a large number of responses to managing increasing flood risk due to climate change (more than 80 were considered in the Foresight Future flooding project), encompassing structural and non structural measures. There are growing volumes of guidance and tools to assist in the selection of responses. In general, for professional practitioners, the responses and effectiveness are apparent and given baseline information, such as rainfall uplifts, changing risks can be dealt with provided the resources are available.

A major problem, however, is the site specificity of effectiveness for responses. In the local drainage area the institutional barriers may be the most problematic. Hence, it is imperative to try to build capacity in each of the stakeholder groups (Table 1) involved in flood risk management and invest in building the potential to respond to changes in future risk.

The €10M FLOWS project (Floodplain Land Use Optimising Workable Sustainability) funded by ERDF through the Interreg IIIB North Sea Region programme has recently been completed [http://www.flows.nu/modules/module_123/proxy.asp?D=2&C=35&I=9&mnusel=8a] and included a number of major elements of capacity building amongst stakeholders. Included in the outputs is a web based interactive learning tool providing an innovative approach to disseminate flood information, targeting particularly land use planners, water managers and the public. The project also utilised 'Interactive Learning Groups' (ILG); an interactive learning process. Comparison with traditional 'focus groups' showed that ILGs were more successful at developing an understanding of flood risks than the focus groups for those with no experience of flooding. However, there was a general outcome that indicated that 'people cannot imagine flooding actually happening' and 'the consequences of flooding if it does happen will not be very severe'.

In the AUDACIOUS project most of the case studies have been carried out in the BMDC area (see 4). Capacity building has been undertaken in a number of ways simultaneously as illustrated in Table 2.

Stakeholder engagement activity	Engaged with and how	Impact
BMDC flood and water management inquiry	Every conceivable stakeholder. Meetings, group workshops, presentations. School education activities. High media profile final conference.	Raised political awareness at all levels, including government. Reached some previously unreachable stakeholders (e.g. Health Trusts). Helped build capacity in professional groups across departments within BMDC.
Establishment of a number of FLAPs (Flood: Local Action Plans)	Local residents and land owners with known local flood risks.	These are areas where the local residents or landowners are themselves responsible for managing local flood risk. Helped by providing information to assist responses and prepare better for flooding.
Establishment of a Water Management Advisory Group	Includes all major stakeholders (not public)	Greater cooperation in planning for flood risk management. Joint R&D project proposals and activities.
Public fora at specific locations	Local residents and land owners with known local flood risks.	These have been held in areas where the flood risks may be the responsibility of the key stakeholder agencies. The fora
Web site http://www.bradford.gov.uk/environment/environmental_protection/water_management/types_of_flooding.htm	Local community with information, history and updated meeting minutes etc.	Increased awareness of who key stakeholders are and their responsibilities. Where/who to contact for information and help.

Table 2 Activities across stakeholder groups by BMDC to build capacity to respond to local urban flood risk

Adapting on a large scale is also going to require different approaches to urban area planning. The ASSCUE project has developed better methods for accounting for urban land form, using for example, green/flood corridors. At the extreme, these may require the relocation of communities, a concept proposed for the future vision for Rotterdam (Geldof, 2006). Future responses need to be adaptive if they are to cope with the increasing complexity in the future, spanning not only flood risk management, but also water quality and in many places, water scarcity.

For Rotterdam there is a high awareness in general about future risks due to rising sea levels in particular. In AUDACIOUS a study has been undertaken to determine how best to increase capacity and awareness among the Class A stakeholder community (Table 1) (Jackson, 2005). This concluded that:

- there were significant suspicions about the major stakeholders' effectiveness and reliability (this was because of broken promises by the EA following main river flooding)
- there is a need for local communities to be coherent and to be able to lobby effectively to obtain resources for either flood risk reduction or for local support measures (especially influencing RFDCs)
- the EA's 'Flood Pact', designed to provide a generic base for Parish Councils or their equivalent was a good model that could be built upon to develop local FLAPs, however, these need local facilitation by an expert
- local communities or individuals with no apparent history of flooding have little interest in developing responsive capacity even where the risk is shown to be increasing.

4. Case studies

There are a number of on-going studies that have not yet been completed. These are based in the BMDC area and are currently dealing with known flood risks, typically where flooding has occurred within the past 5 years. These are listed in Table 3.

4.1 Factory building and St Andrews school 'downstream'

With a possible link to the flooding problems experienced at the nearby St Andrews school, the factory building located in Haggas Lane, Keighley provides an example of a combined (i.e. roof and collection) system that is prone to surcharge during significant rainfall events. Collating information from drawings, from Mastermap and from on-site observations and interpretations, a representative system schematic for the multi-section roof and small-scale local drainage was developed that facilitated a performance analysis following application of the enhanced building drainage model. Gutter and gulley sizing was undertaken in accordance with appropriate standards (EN 752, EN 12056) and current rainfall datasets representing those for a return period of 10, 30 and 100 years were defined using the Flood Estimation Handbook (CEH, 1999). Two event durations were set, 15 minutes and 30 minutes, and then uplifts of 1.2 and 1.4 were initially applied to represent future climate change scenarios.

Location	Sources	Properties affected	Actions
Mill Hey, Haworth	River Overland flow Surface sewers Combined sewers	20, mainly commercial	Maintenance of river channel. Diversion of flow back to river before it reaches vulnerable properties. Diversion of overland flow around vulnerable area. Once river and overland flow dealt with, assess situation for surface water and combined sewers
Hollins Lane, Utley	Overland flow	12+ domestic	Re-establishment of old ditch system Diversion of flow around local vulnerable areas
Aireville Close/ Manor Road, Utley	Overland flow Combined sewers	2+ domestic	Review pathways and contributing area Review gulley and sewer performance Review routing of flow around properties
Greenhead School, Utley	Overland flow	New development	Assess flood risk and flood impact of new school development proposal
Skipton Road Utley	Overland flow Capacity and maintenance of culvert	20+ domestic	Identify route of culvert. Reinstate culvert Provide source control upstream of problem
Devonshire Park, Utley	Overland flow Capacity and maintenance of culvert Combined sewers	15+ domestic and commercial	Identify route of culvert Reinstate culvert Provide source control upstream of problem Review gulley and sewer performance
Guard House School	Overland flow Combined sewers		Provide surface and sub surface storage. Route flows away from school to water course. Assess flood risk and flood impact of new school development
St Andrews school	Overland flow Combined sewers		Provide surface and sub surface storage to protect school Route flows away from school to watercourse
Major building society headquarters	Non-critical watercourse On-site drainage	2 major buildings Consequence £1Ms	Increase conveyance of watercourse Planned exceedance pathways

Table 3 BMDC area case studies

Simulation results showed that overtopping of the roof drainage is predicted in a number of gutters subject to even the lowest of flow loadings (i.e. those representing a short return period and current conditions rather than those indicative of climate change impacts), thus confirming observations. Overtopping in these same gutters increases when return periods are longer and uplifts have been applied. Reasons for overtopping are the high exposure to wind driven rain and a lack of capacity of downpipes relative to the associated roof area. The model also simulates the degree of interaction exhibited by multiple gutters and downpipes. This illustrates how higher intensity rainfall events do not necessarily proportionally increase the degree of overtopping in the same gutters, and how accurate simulation models are therefore required to predict system performance.

In the Haggas Lane case study example, the adaptable input system and the ability of the model components to represent flow interactions allowed an assessment of the impact upon performance of system adaptation strategies. These included, as examples for roof drainage, the re-allocation of gutter depth dimensions and the replacement of impervious roof surfaces with a pervious or 'green' covering.

With the local (curtilage) drainage model predicting surcharge volumes under the same range of rainfall events, performance under both current and predicted climate change scenarios was determined. Clearly, surcharge volumes determined using the larger of the uplifts were greater. Here, combined flows and pipe capacity are the main determinants in defining excess surcharge volumes, and adaptation solutions included the introduction of ‘offline’ storage facilities connected at gully inlets, where this storage is initiated by the occurrence of full bore flow in the connected pipe leading to ‘spillover’.

The use of this case study clearly illustrates the applicability of the enhanced model in determining system performance under both current and predicted rainfall scenarios, and, importantly, in assessing the potential beneficial impact of proposed adaptation strategies.

It is possible that for economic reasons, the factory owners may wish to manage risk and upgrade the roof drainage system without the provision of storage. It should also be noted that the standards for roof drainage are in any case higher than for car park drainage and excess flows will have to be managed on the surface. There is also the need to consider that Yorkshire Water has only just enhanced the sewer system and that they and their stakeholders may have higher priorities than carrying out further enhancements on the basis that climate change may increase precipitation. What does this mean? This is what it means:

“*This mornings’ thunderstorm has generated further complaints amongst which our attention was drawn to the discharge of large volumes of water from Haggas's factory off North Dean Road from what appears to be surcharging drains/blocked or inappropriately positioned gullies collecting a large amount of water from the weaving shed's/warehouse roof. This is overwhelming the gullies protecting Cashmere St and the School. Could be a major contributor to overall problem?*”

The school yard was flooded to a depth of one metre in front of the school and flood water leaked into the school, causing damage to the kitchens and dining room. Fortunately it was the summer holidays, but had it been in term time, the families of 400 children would have been disrupted for a week whilst the school was cleaned up.

The immediate response has been to re-profile two drop crossings and increase the capacity of gullies connecting to the combined sewer. The work carried out by Yorkshire Water had in effect provided additional capacity of the sewerage system, but there was no analysis carried out prior to the construction of additional and larger gullies and so it is not known if these gullies will allow water to flood out of the sewers and on to the highways at a greater rate, or if the water entering the sewer will cause problems downstream. Since the initial response, a design to route flow round the school and into the nearby ordinary watercourse has been devised. This includes storage to compensate for the loss of the flooded area, so as to ensure that downstream problems are not exacerbated.

4.2 Flooding caused by runoff from permeable areas

Elsewhere there has been frequent flooding at several locations on the hillside at Utley, to the north west of Keighley town centre. Overland flow is a major component of the flooding and much of the flooding is related to inadequate capacity and blockage of highway drains and small stream culverts, rather than the sewerage system. In this case, BMDC has had to take an overview of the problem, despite individual land and property owners having responsibilities. However, it is not possible for them to develop effective solutions in isolation.

At some locations the flood volume is so small that there will be no downstream impact if flows are simply routed round the problem, providing that they are routed to the current pathway, defined using GIS and LIDAR surveys. In other areas, the problem is so significant that BMDC as a land owner is providing storage so as to avoid the need to reconstruct stream culverts to provide greater capacity. This approach also sits with the need to ensure that the flooding problem is not simply passed downstream. Simple pragmatic methods using depth of rainfall have been adopted for calculation of storage volumes.

Solutions to the problems include the cleansing and reconstruction of culverts where these have been blocked or lost, the re-establishment of land drainage ditches where these have been obliterated to widen highways, the construction of sealed trench/trough drainage structures to provide storage, and reduce water logging whilst ensuring that groundwater levels are not depleted so as to ensure that trees are not adversely affected. As well as the assessment of economic, social and environmental aspects of flood risk, health aspects have also been investigated

A socio-demographic profile for each case study location was created using the Maps and Stats website (http://www.mapsandstats.com) which allows incomplete output areas to be combined from user-defined areas (providing either a certain number of houses are selected or a target population is achieved – to maintain the individual anonymity provided by output areas).

Mental health problems, characterised as psychological distress, were estimated for adults. Due to the long duration of these problems the YLD scores were greater than for the combined physical symptoms, with 0.582 being estimated for Utley and 0.332 estimated for Devonshire Park. Table 4 outlines the estimated DALYs as a result of flooding in the case study areas.

Area	Deaths (YLL)	Serious Injuries (YLD)	Other physical symptoms (YLD)	Mental health symptoms (YLD)	Total (DALYs)	DALYs/ household	DALY/hh / year
Utley (Hollins Lane)	0.03	0.01	0.006	0.36	0.405	0.034	0.0034
Utley (Skipton Road)	0.03	0.01	0.005	0.22	0.264	0.033	0.0033
Devonshire Park	0.05	0.02	0.007	0.33	0.407	0.040	0.004

YLL – Years of life lost
YLD – Years lived with a disability

Table 4 Health impacts of flooding

The DALY scores presented above for the current situation, when expressed as per person/year (assuming an occupancy rate for Utley and Devonshire Park of 2.4 and 3 people per household respectively) are approximately 0.0013. This is roughly equivalent to those affected each having their life span reduced by 11 hours! It is also possible to compare these DALY scores with those from road traffic incidents. In 2004 there were 115 deaths in children under the age of 16, and 3186 in adults; these figures equate to rates of 9.7/million in children and 66.3/million in adults. Applying these rates to the each case study population (i.e. 226 in Utley – Beechcliffe; 261 in Utley – Hollins Lane; 553 in Devonshire Park) and assuming an average age at death of 8 in children and 45 in adults, it is estimated that the areas would suffer between 0.42 and 1.01 DALYs as a consequence of road traffic accidents.

5. Implications for main drainage

It was identified in section 3.9 that local solutions need to be considered in the context of the wider urban drainage system. Approaches for the development of transparent storm and surface water management plans through the collaboration of local authorities, sewerage undertakers and drainage authorities have been described by Blanksby et al (2005). This has been further developed by Defra (2006) and will become one of the main subjects to be investigated in the Making Space for Water pilot studies. One of the results of integrated assessments and studies is the possible development of appropriate planning policies and guidance for developers and there are potentially major benefits in this as adaptation at a local scale may produce a significant contribution to the overall management of flood risk.

6. Conclusions

Potentially the outcomes from the AUDACIOUS project are relevant to each one of us. The project has developed tools and methodologies to help with the examination of both current flood risk in local areas and future changes in risk as a consequence of climate change and other effects such as urbanisation, changes in lifestyle and expectations. AUDACIOUS is intended to promote the use of responses that comprise 'adaptable solutions' rather than the current robust approach that tends to concentrate solutions on single point 'big-fix' solutions that are irreversible and lacking in future flexibility. Given the uncertainty of the likely major climatic changes, particularly rainfall, or in future adaptive capacity to cope with these changes (e.g. capacity is typically related to wealth, IPCC, 2001), it is important to provide flexible approaches that can evolve as knowledge develops. AUDACIOUS is a contribution to this.

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