Using climate change projections in UK flood risk assessment

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In the UK, a disparity exists between modelled future weather/climatic patterns and the assessment of climate change impact on flood risk in the UK statutory planning process. Specifically, the impacts of climate change on the physical characteristics of a river catchment (e.g. land-use change, vegetation cover, soil moisture) are not considered when generating climate change weighted design flood events to assess the potential impact of flooding on a development in the future. Instead, a UK-wide averaged perturbation factor is applied. In this paper, a method is tested to integrate climate change data from UK climate projections 2009 (UKCP09) into design flood estimation methods (ReFH) as part of the current planning process. Scenarios are developed for a single, critical duration, 1% probability (1-in-100 year) design flood event that reflects plausible changes in catchment physical parameters in the 2080s. Initial results suggest that a 1-in-100 year storm in the 2080s may be greater in magnitude, rise and recede faster, and be associated with greater depths of flooding than predicted using current flood risk assessment frameworks in the UK. This information could provide new information to help developers choose more sustainable, flood-resistant and resilient designs.

1. Introduction

UK climate change projections provide a wealth of information about how the climate will change in the future (Murphy *et al.*, 2009). Among many common climate variables including temperature and precipitation, the projections also include soil moisture changes, humidity variations and storm frequency. These projections are available for a range of future horizons and, in many cases, the projections are probabilistic. A number of studies have taken these data to assess the possible future impact of climate change on rainfall intensity flooding (see works by Prudhomme *et al.* (2003), Ashley *et al.* (2005), Kay *et al.* (2006), Wilby *et al.* (2008) and Prudhomme *et al.* (2010) and references therein).

Current flood estimation techniques generally used by planners and developers utilise empirically derived relationships captured within the *Flood Estimation Handbook* (FEH) (IOH, 1999) to model rainfall–runoff as a storm hydrograph (ReFH) (see Kjeldsen *et al.* (2007) for further information). The ReFH method is able to produce storm hydrographs for a range of return periods within a catchment. These design floods can then be used as input boundary conditions within flood models as part of the flood risk assessment process. This process in itself is known to associate lower frequency rainfall events with flood events of a specific frequency (e.g. 1 in 100 years). It also does not assess any effects of the temporal distribution of rainfall that will drive unique groundwater responses that may significantly impact the rainfall–runoff relationship, particularly for permeable catchments (Faulkner and Barber, 2009; Wheeler *et al.*, 2002).

Statutory UK planning regulations such as Planning Policy

Statement 25 (PPS25) (DCLG, 2006) require climate change impacts on 1-in-100 year design floods to also be accounted for as part of the flood risk assessment process within UK planning regulations for new developments. PPS25 states that the impact of climate change across all of England will be realised as 20% increases in 1-in-100 year river flows from 2025 to 2115 (DCLG, 2006). This percentage is derived from averaged, deterministic climate change projections for England from the UK climate change impact project 2002 (UKCIP02) (Hulme *et al.*, 2002). This weighting does not account for the impact climate change will have on the physical properties of the responding catchment. It also does not take into account any regional socio-economic variations that may also perturb the current relationship between rainfall and runoff (Rodda *et al.*, 2010; Sefton and Boorman, 1997). Generally, future climate projections suggest wetter winters and drier summers for England. This change in climate will also alter the antecedent conditions of the catchment and may produce very non-linear responses within a river to projected increases in rainfall within the catchment for a design flood event. For example, a drier catchment may allow more rainfall to infiltrate local soils and act to reduce the percentage of runoff from the catchment and mitigate some of the projected increase in rainfall during a 1-in-100 year storm. Equally, wetter soils will have less capacity for rainfall infiltration, and runoff and river flows may increase relative to rainfall.

Recent research into the FEH has shown disparities between the DPLBAR descriptor (mean drainage path length; see Kjeldsen *et al.* (2007) for further information) exported from FEHv3 (CEH, 2009) and that calculated from more recent data sources (such as higher resolution digital terrain models (DTMs) than the IHDTM

within FEHv3) (Flather, 2010). Changing patterns of urbanisation have also not been captured in the FEHv3 CD-Rom and have resulted in the proposed use of an urban adjustment parameter to account for recent changes in urbanisation (Bayliss *et al.*, 2006). This suggests that subsequent flood hydrograph estimation using ReFH (CEH, 2007) could misrepresent a catchment's response to a design flood event in the future. This misrepresentation of future catchment responses to rainfall has been detailed by Reynard *et al.* (2009), whose research has highlighted that the 20% climate change allowance is often not precautionary and that catchment properties (characterised as specific catchment descriptors in FEH) have a significant impact on how a catchment responds to rainfall and generates runoff under climate change.

In this paper, a method to incorporate extra climate change data within current flood estimation frameworks (i.e. FEH–ReFH design event storm hydrographs) is proposed and trialled. The method is applied to the River Cam at Hinxton. This site was chosen as a research centre on the River Cam at this location is a new development (opened in 1996), designed to be located above the 1-in-100 year flood level for the design life of the building.

The River Cam is gauged 2 km up-river of Hinxton at Chesterford (National River Flow Archive reference number 33051) (CEH, 2013) but the dataset has not yet passed quality assurance and control guidelines to ensure validity. For the planning application for this site, the flood risk assessment did not rely on statistically derived return period events from long-term monitoring, but utilised Environment Agency (EA) flood maps and flood levels from the EA flood modelling in addition to historical flooding data that supported the assessment that the site was outside the predicted 1-in-100 year flooding envelope (Faber Maunsell, 2008).

Two climate change scenarios are developed for the 2080s by altering specific FEH catchment descriptors to account for the impact of climate change on the physical properties of the catchment utilising data from UK climate projections 2009 (UKCP09) (Murphy *et al.*, 2009). These scenarios are compared to two scenarios that use the current FEH catchment descriptors (baseline and PPS25). 1-in-100 year (1% probability) storm hydrographs for each scenario are modelled using ReFH (CEH, 2007). The ReFH hydrographs are then used as input conditions to a two-dimensional (2D) hydrodynamic floodplain model of the River Cam at Hinxton using 1 m resolution LiDAR topographic

data (EA, 2013a) to analyse the resultant variability in a design 1-in-100 year flood along this stretch of the River Cam.

2. Background

The issues of river and surface water management, drainage and flood risk are covered by a range of European Union directives, UK parliamentary acts and environmental legislation at local, regional and national scales. These include the EU flood risk directive 2007/60/EC (EC, 2007), the water framework directive 2000/60/EC (EC, 2000), the UK Floods and Water Management Act (Floods and Water Management Act, 2010), Planning Policy Statement 25 (DCLG, 2006) and Technical Advisory Note 15 (Welsh Assembly Government, 2004).

Integrated into most of these policies is the risk of climate change and guidance on how to include, account, assess and mitigate its effects. In terms of flooding, the most relevant policies and guidance include the flood risk directive, the UK Floods and Water Management Act 2010, Planning Policy Statement 25 and 'Future Water' (Defra, 2008).

Planning Policy Statement 25 (PPS25) (DCLG, 2006) is the key reference document with respect to flood risk, climate change and development in the UK. In particular, the document outlines climate change perturbations to be used to assess a new development's risk from river flooding from a 1-in-100 year design flood event (Table 1). PPS25 provides a risk-based framework within which to

- assess the risk of a new development to flooding for its designed lifespan
- champion flood-resilient design
- develop flood alleviation schemes where appropriate
- give assurance that the development does not increase the risk of flooding down-river of the proposed development.

PPS25 does this through the requirement to use a climate change perturbation factor to increase the severity of a 1-in-100 year design flood event. The perturbation factors are derived from spatially averaged climate change impacts data from the non-probabilistic UKCIP02 climate change projections (Hulme *et al.*, 2002) for England (see DCLG (2006, 2007) for further information on the PPS25 application of the UKCIP02 data).

There is now, however, a disconnection between the recommendations of PPS25 to include an assessment for future climate change

	1990–2025	2025–2055	2055–2085	2085–2115
Peak river flow: m ³ /s	+10%	+20%	+20%	+20%

Table 1. Perturbation factors used to weight historical records (1961–1990) for the effects of climate change. The amount of perturbation is dependent on the designed lifespan of the development (DCLG, 2006)

impacts on the flooding risk to a new development (using spatially averaged UKCIP02 climate change impact projections) and spatially discretised climate change projections from the latest UK climate projections (UKCP09) (Murphy *et al.*, 2009). In particular, there is a mismatch between the projected peak rainfall changes from climate modelling (UKCP09) and the perturbation factors being applied by PPS25 (i.e. a 20% increase in 1-in-100 year flows in 2025–2115 across the whole of the UK), and a failure to recognise any changes in antecedent ground conditions provided by the UKCP09 projections. The PPS25 approach also does not account for future changes in catchment urbanisation and farming practices that may result in unexpected response by the catchment to projected changes in peak rainfall. For example, the wetter future winters predicted by UKCP09 may compound increases in peak storm rainfall and result in higher river flows than currently expected using the PPS25 approach. The Appendix briefly outlines climate change projections for a range of physical parameters from UKCIP02 (Hulme *et al.*, 2002) and UKCP09 (Murphy *et al.*, 2009) and compares them to PPS25 where appropriate. Further description of the differences between UKCIP02 and UKCP09 are available elsewhere (Met Office, 2012).

Another significant difference between PPS25 climate change perturbation and the results from climate modelling is spatial complexity (Boorman and Sefton, 1997). Changes in rainfall patterns, temperatures, cloud cover, humidity and many other climatic variables are spatially heterogeneous (Murphy *et al.*, 2009) but the perturbation factors in PPS25 are generalised across England.

The final disconnect is that of rainfall return periods. Recent analysis and extrapolation of rainfall return periods using UKCP09 projections has shown that the frequency of higher magnitude, lower probability rainfall events is increasing. In the

case of Cambridge, a current 1-in-100 year (1% probability) magnitude event is likely to occur much more frequently in the future – occurring every 1 in 40 years (2.5% probability) by the 2040s and as frequently as 1 in 25 years (4% probability) by the 2080s (Sanderson, 2010; see Figure 1). From a planning perspective, this means the risk of flooding (due to rainfall–runoff) may significantly increase during the lifecycle of a building. Detailed modelling of the impact of climate change on flood frequency across 154 UK river catchments (Reynard *et al.*, 2009) shows that all catchments neighbouring the River Cam at Hinxton are likely to see increased magnitude flows for 1-in-50 year events as a result of climate change (see figure 4-3 in the work of Reynard *et al.* (2009)).

Aspects of these limitations have been investigated. A recent study investigated the impact of changes to the FEH descriptor DPLBAR. Geographic Information System (GIS) analysis of the most recent Ordnance Survey maps was used to calculate the changes in this descriptor resulting from the increase in field sizes between 1958 and 2008. The study showed that the changes between 1958 and 2008 for three catchments reduced runoff time-to-peak and increased peak discharge (Flather, 2010), which is not captured in the current FEH descriptor. Bayliss *et al.* (2006) took a similar approach to modifying the FEH, introducing an urban adjustment factor (UAF). This new descriptor was then used to model the change in response of a catchment to rainfall accounting for increased urbanisation. Rodda *et al.* (2002) also suggested that the current approach to extreme event estimation is limited by the fact that only rainfall extremes are taken into account, when in fact extreme soil moisture deficits may compound or mitigate the severity of such events.

This section has highlighted some of the disparities between our current understanding of changing hydrological regimes in the UK and implementation of this knowledge within the planning

Figure 1. Reclassification of 1-in-5, -10, -20, -30, -50 and -100 year events from now to the 2080s in Cambridge (Sanderson, 2010)

process guided by policies such as PPS25. In this paper, a method that includes further aspects of this climate change information within current flood estimation frameworks is trialled. The purpose of this study is to assess whether current flood estimation frameworks can be adapted to include more climate change information without the need for downscaling regional climate models. Furthermore, the trial was designed to assess if the results would have provided different assessments of flood risk that could have driven different approaches to the location and design of the studied development.

Two scenarios are developed: the low-impact and high-impact climate change future (Fut-Low and Fut-High) represent different realisations of a 1-in-100 year flood event in the 2080s. These scenarios are compared to a current 1-in-100 year baseline scenario and a PPS25 weighted scenario for the same planning horizon.

3. Materials and methods

3.1 The River Cam at Hinxton

Catchment descriptors for the River Cam at Hinxton were exported from FEHv3 CD-Rom (CEH, 2009) at grid reference 549638 243845 (TL496438), a location 1 km upstream of the town of Hinxton, Cambridgeshire (Table 2). The River Cam catchment at Hinxton is 148.99 km² in area and is essentially rural except for

the town of Saffron Walden, 7.2 km upstream of Hinxton. Mean yearly rainfall for the standard period (SAAR) (1961–1990) is 598 mm. At this location, the River Cam catchment has a BFIHOST (baseflow index–hydrology of soil types) value of 0.583, suggesting almost 60% of flow at this point is derived from baseflow – a characteristic feature of a permeable catchment (Boorman *et al.*, 1995; Lee *et al.*, 2005). An SPRHOST value of 30.1 suggests that a little over 30% of rainfall is direct runoff to the River Cam, which again is indicative of a catchment underlain by areas of chalk bedrock with high infiltration potential. The mean catchment slope (DPSBAR) is 40.6 m/km, giving a very gentle average slope of just 4%. This also helps to reduce direct runoff and increase infiltration as indicated by the BFIHOST and SPRHOST values.

3.2 Weighting catchment descriptors

The general consensus on climate change impacts from both historical trend analysis and future modelling for the UK is drier summers and wetter winters (Murphy *et al.*, 2009; Orr and Carling, 2006), with many areas becoming dryer overall by the 2080s. Without complex catchment-scale hydrological modelling from downscaled regional climate models there is little opportunity to utilise UKCP09 data within the current flood estimation frameworks. This trial method uses information from the 50% probability UKCP09 projections to perturb the PROPWET,

FEH descriptor	Description	Value
AREA	Index describing catchment area: km ²	148.99
FARL	Index describing flood attenuation in catchment from lakes and reservoirs (lower number = greater attenuation)	0.993
PROPWET	Index describing the proportion of time catchment soils are wet	0.29
ALTBAR	Index describing mean catchment altitude: m AOD	92
ASPBAR	Index describing mean catchment slope aspect	181
ASPVAR	Index describing the invariability of catchment aspect	0.03
BFIHOST	Index describing contribution of groundwater to flow derived from the hydrology of soil types (HOST)	0.583
DPLBAR	Index of catchment orientation and flowpath length	13.78
DPSBAR	Index of mean catchment steepness: m/km	40.6
LDP	Longest drainage path in catchment: km	24.36
SAAR	Mean annual rainfall for the standard period (1961–1990): mm	598
SAAR4170	Mean annual rainfall for the period 1941–1970: mm	610
SPRHOST	Index describing percentage runoff derived from HOST	30.8
URBCONC	Index describing the concentration of urban and suburban landcover	0.601
URBEXT1990	Index describing fraction of catchment urbanised in 1990	0.018
URBLOC	Index of location of urban and suburban landcover	0.863
RMED-1H	Mean annual maximum 1 h rainfall: mm	10.7
RMED-1D	Mean annual maximum 1 d rainfall: mm	29.
RMED-2D	Mean annual maximum 2 d rainfall: mm	36.6
Grid reference	Ordnance survey grid reference	549600 243750

Table 2. Key FEH catchment descriptors for the River Cam at Ickleton Weir (U/S of Hinxton) (further information on the catchment descriptors is given in the FEH (IOH, 1999))

BFIHOST, SPRHOST, DPLBAR and URBEXT1990 catchment descriptors (Table 2).

These descriptors were chosen as they offer an opportunity to capture

- the effect of wetter antecedent conditions (PROPWET) on direct runoff (SPRHOST) and the resultant increase in proportion of surface water runoff to baseflow (BFIHOST) as described in the 50% probability UKCP09 climate change projections for the UK (Murphy *et al.*, 2009)
- socio-economic changes within the catchment from increases in field sizes (DPLBAR) based on observed changes in other UK catchments (Flather, 2010) and an author-chosen urban expansion (URBEXT1990) for the Fut-High scenario only
- the increase in frequency of current return period rainfall events resulting in an increase in magnitude of a 1-in-100 year return period event (Sanderson, 2010).

3.3 Scenarios

The Fut-Low scenario takes a current 1-in-125 year return period rainfall event to be the same as a 1-in-100 year event in 2080 (Table 3). The catchment descriptors SPRHOST, BFIHOST, PROPWET, DPLBAR and URBEXT1990 are altered to reflect the environment in this more benign future scenario. Slightly increased runoff (SPRHOST) and wetter soil conditions (PROPWET) are anticipated to increase runoff slightly, but a similar amount of baseflow (BFIHOST) is expected. Slightly larger field sizes are expected compared with the situation in 2009 when FEHv3 was published. No extra urban development is anticipated in this scenario (Table 4).

The Fut-High takes a current 1-in-150 year rainfall event as a 1-in-100 year flood event in the 2080s (Table 3). Soil wetness and runoff are considerably greater in this scenario and slightly less flow proportionally is expected from baseflow, further reflecting a greater proportion of surface water runoff due to the higher intensity of rainfall. More intensive agriculture is expected in this scenario and field sizes slightly increase accordingly. A small amount of urban expansion is also expected (Table 4).

The baseline scenario takes the current catchment descriptors from FEHv3 CD-Rom and a 1-in-100 year storm hydrograph is modelled in ReFH. The PPS25 scenario is the same as baseline scenario except the storm hydrograph is multiplied by 120% to account for future climate change as required by PPS25 (DCLG, 2006).

3.4 Floodplain model

A hydrodynamic 2D floodplain model was run using the IBER model developed at the Technical University of Catalonia (TUoC, 2010). This model solves the 2D Saint-Venant equation to calculate hydrodynamic flow using a shock-capturing explicit high-resolution finite-volume method (Bladé *et al.*, 2008; TUoC, 2010). Input model boundary conditions are defined by the storm hydrograph output from ReFH for the four scenarios. The downstream boundary condition for the northern edge of the modelling domain is represented as a weir with coefficient 1.6 across the whole northern boundary of the DTM (TUoC, 2010). This was done to prevent artificial water accumulation along the edge of the DTM (TUoC, 2010). Manning's n values of 0.035 are used to represent both the river channel and flood plain in the IBER model (TUoC, 2010).

Scenario	Return period: years	Duration: h	Season	Additional information
Baseline	100	15.5	Winter	Current catchment descriptors
PPS25	100 + 20%	15.5	Winter	Current catchment descriptors
Fut-Low	125	15.5	Winter	Low scenario catchment descriptors
Fut-High	150	15.5	Winter	High scenario catchment descriptors

Table 3. Hydrological conditions for a critical-duration 1-in-100 year storm at Hinxton for the four scenarios

Descriptor	Baseline and PPS25	Fut-Low	Fut-Low change: %	Fut-High	Fut-High change: %
SPRHOST	30.8	32.34	+5.0	35.57	+10.0
BFIHOST	0.583	0.583	+0.0	0.56	-5.0
PROPWET	0.29	0.30	+5.0	0.33	+10.0
DPLBAR	13.78	13.44	-2.5	12.40	-10.0
URBEXT1990	0.018	0.018	0.0	0.019	+7.5

Table 4. Catchment descriptors for the baseline, PPS25, Fut-Low and Fut-High scenarios

A 1 m resolution DTM with vertical accuracy of ± 15 cm was used (EA, 2014) to limit errors associated with lower resolution grids (Haile and Rientjes, 2005). For computational efficiency, modelling outputs were generated on a 4 m irregular triangular mesh generated from the DTM across the entire modelling domain. The river channel is defined by a 2 m irregular triangular mesh that extended 25 m perpendicularly from the top of left-hand and right-hand banks respectively. Where the channel passes through constrictions such as a railway crossing, a 1 m irregular triangular mesh is used 20 m up- and down-river of the constriction and extending 15 m perpendicularly to improve modelling of any throttling or surcharging of flows. Model outputs were written at 5 min intervals for water depth (m), water velocity (m/s) and water surface elevation (m AOD).

3.5 Key assumptions

To enable completion of this modelling work, the following key assumptions were made.

- The storm hydrograph outputs from ReFH are assumed to be fit-for-purpose and representative of storm hydrology within this section of the River Cam as is assumed under current UK planning frameworks.
- Modelling the northern boundary of the modelling domain as a weir set to the elevation of the DTM will act to not artificially impede flow within the channel and surrounding floodplain, or convey water too easily from the modelling domain.
- This study is investigating the impact climate change might have on a catchment for a design flood event that is not currently captured in the modelling of design flood events. The study is not investigating flooding from an observed event so no calibration/validation of the 2D hydrodynamic model is completed for this stage of the research. Visual comparison of the baseline scenario with the EA indicative flood maps for the River Cam at Hinxton has been completed.
- Capture of the 1 m resolution DTM from airborne LiDAR occurred at a time of low flow (summer) to sufficiently capture the morphology of the River Cam channel for the purposes of the 2D modelling.

4. Results and discussion

4.1 Rainfall-runoff modelling (ReFH)

Catchment descriptors from FEH were imported into ReFH and used to generate storm hydrographs for the River Cam approximately 1 km upstream of Hinxton (Table 2).

Initial results show the peak flow of the Fut-High scenario storm to be much greater than the other three scenarios. The PPS25 scenario has similar peak flows when compared to Fut-Low. The baseline scenario has the lowest peak flows of the four scenarios.

The time-to-peak of Fut-High (7.89 h) is faster than PPS25

(9.77 h) and Fut-Low (9.22 h). The total response time of the catchment in the Fut-High (43.5 h) event is approximately 7 h faster than PPS25 (50.5 h) and 5 h faster than Fut-Low (48.5 h) (see Figures 2 and 3).

Initial results from the Fut-High scenario suggest that, for the River Cam at Hinxton, climate and land management changes will not only result in greater peak river flows, but a much quicker catchment response and shorter overall storm hydrograph (Figure 2). Similar results were found for the Fut-Low scenario. Fut-Low peak flows are less than those for Fut-High and PPS25, but time-to-peak and overall catchment response times are quicker than the baseline and PPS25 scenarios.

From a developer's perspective these results have two immediate implications. The first is that the overall extent of flooding for a 1-in-100 year event in the 2080s may be greater than the current PPS25 estimates predict and therefore a level of flood protection built now, based on the PPS25 scenario, may be insufficient to prevent flooding from a 1-in-100 year flood in the 2080s. The

Figure 2. ReFH flow hydrographs for the baseline, PPS25, Fut-Low and Fut-High scenarios for the River Cam U/S Hinxton

Figure 3. Histograms of key characteristics of the four scenarios modelled in ReFH

second is that, under both the Fut-High and Fut-Low scenarios, the River Cam is more responsive to rainfall, with flood peaks occurring sooner than for the baseline and PPS25 scenarios.

To investigate the potential impact of these different scenarios on flood depths and extents at Hinxton, the storm hydrographs for the baseline, PPS25, Fut-Low and Fut-High scenarios were modelled as input boundary conditions to a 2D hydrodynamic floodplain model using IBER.

4.2 Floodplain modelling

4.2.1 Results

The baseline scenario provided a frame of reference to assess the performance of the IBER model with current EA flood mapping for the area. In general, the modelling is in good agreement with EA indicative flood maps (Figure 4). Resultant flood extents from 1.5 h, 6.5 h, 11.5 h, 14.5 h and 17.5 h/19.0 h were output for each scenario and qualitatively compared (Figure 5).

At the start of river flooding (1.5 h) the overall extents increase from baseline, PPS25, Fut-Low and Fut-High, with the latter three having significantly greater flooding extents than the base-

line. This is particularly true in the pond immediately to the northwest of the research centre in Fut-Low and Fut-High scenarios (Figure 5).

At the second time index (6.5 h), PPS25 and Fut-High, and baseline and Fut-Low have similar spatial flooding extents. This is a slightly unexpected, especially for baseline and Fut-Low scenarios given the greater flows associated with Fut-Low (Figure 2). In general, flooding is mainly associated with the floodplain to the west of the research centre. Other areas of flooding occur along the eastern edge of the railway line and a small amount of flooding is seen to the west of the sewage works (Figure 5).

At the third timestep (11.5 h) flooding in PPS25, Fut-Low and Fut-High are significantly greater than the baseline scenario. Flooding is most extensive in Fut-High, followed by PPS25, Fut-Low and baseline. At this timestep, PPS25 and Fut-Low are quite similar. Flooding has begun to occur in the wetland south of the research centre (see area marked 3 in Figure 4 to locate) and there is significant water in the ponds to the northwest of the research centre. Significant flooding in the floodplain adjacent to the research centre is also visible, although water depths are

Figure 4. Comparison of flooding extents from Environment Agency (EA, 2013b) (b) and this study (a) for a 1-in-100 year flooding envelopes along the River Cam at Hinxton. EA indicative

flood maps are generated from a 2D hydrodynamic model using JFlow with a 5 m resolution NextMAP DTM and inflows generated using the same FEH-ReFH approach (Halcrow, 2010)

Figure 5. Maps showing depth and extent of flooding at across the Hinxton floodplain for the four scenarios developed

generally low. Some flooding is also present immediately west of the sewage works. For PPS25 and Fut-Low, the River Cam has also just started to breach its banks in the region of area 1 (see Figure 4 for location). In the baseline scenario, this has not yet occurred. The extent and depth of flooding in the region of area 3 is greater in Fut-High than in Fut-Low and PPS25 (which are very similar), and significantly greater than in the baseline scenario.

By the fourth timestep (14.5 h) flooding extents in Fut-High continue to be much greater than in Fut-Low and PPS25. Flooding extents for the baseline scenario are significantly less. Flooding extents are similar for PPS25, Fut-Low and Fut-High, although depths are greater for Fut-High, notably in the pond to the northwest of the research centre and on the west side of the railway line where the River Cam is closest to this linear feature. The extent of flooding in the urban area located around this area also shows greater depth and spatial extent for Fut-High, with similar extents and depths being associated with Fut-Low and PPS25.

The trend from the fourth timestep continues into the fifth (17.5/19.0 h) when maximum flooding is experienced. As with the previous two timesteps, PPS25 and Fut-Low are very similar in terms of both flooding extents and flood depths. At this stage of maximum flooding, the baseline scenario is also very similar to PPS25 and Fut-Low but with lower depths of flooding. The extent of flooding in the region of area 1 is also less in the baseline scenario. Flooding extents and depths for Fut-High are much greater across the modelling domain, particularly in the pond to the northwest of the research centre, in the urban region associated with area 1 and to the west of the railway line where it is closest to the River Cam.

4.2.2 Interpretation

The modelling results are interesting. Spatial depths and extents of flooding suggest that inclusion of climate change as required by the PPS25 framework (PPS25 scenario) related well to the Fut-Low scenario even though their ReFH flood hydrographs were subtly different. The major difference between PPS25 and Fut-Low scenarios is that waters in the River Cam initially rise more quickly at the start of the event in Fut-Low, but PPS25 causes greater flooding during the mid-component of the rising limb of the hydrograph. This is interpreted as being due to greater volumes of water being modelling in the River Cam. The overall flood peaks are very similar in terms of both depth and extent across the River Cam floodplain at Hinxton. The Fut-High scenario produces significantly greater flooding across the site in terms of both extents and depths. The results for Fut-High are significantly greater than the PPS25 and Fut-Low scenarios.

These results highlight a number of potential problems with the current assessment of how resistant and resilient a building such as the studied research centre (Figure 4) will be to flooding during its lifetime. The results from this study show that the

coupled impact of more intense rainfall and changing catchment characteristics may result in futures similar to what we are currently planning for under the auspices of PPS25 (Fut-Low). However, the results also show that in another plausible future realisation of the 2080s – Fut-High – there may be significantly greater flooding in terms of both spatial extent and depth.

Although this is a qualitative exercise to investigate the impact of climate and land-use changes on how a catchment will respond to a 1-in-100 year design flood event in 2080, it does show that antecedent physical catchment characteristics will affect how the catchment responds overall if these futures are realised. This research highlights the need for further quantitative assessment of the true impact of future climate and land-use changes and how this can be consistently transposed from UKCP09 to change the FEH catchment descriptors and how climate change would perturb the resultant design flood event modelled in ReFH.

This will also require further investigation of the differences between not only a summer and winter 1-in-100 year rainfall event, but also the magnitude of such events up to the 2080s, which is the current planning horizon for many public and private buildings.

5. Conclusions

This paper has outlined a novel approach to the integration of detailed climate and land-use change data within current flood estimation and modelling frameworks prescribed by the UK planning process for new developments. The results show that – in the case of the River Cam at Hinxton – the current application of climate change predictions to future flood risk assessment as required by PPS25 translates comparably to the Fut-Low scenario developed. However, the results from a plausible scenario outlining a high-impact climate change future centred on the 2080s (Fut-High) show that current estimates may significantly underestimate the magnitude of a 1-in-100 year flooding event.

These results show that there is opportunity to utilise UKCP09 climate change data within current flood estimation methods. There is, however, the need for thorough quantitative research into how this can be best achieved. This is particularly true when thinking not only about the spatial complexity of climate change impacts across the UK, but also the growing disparity between winter and summer rainfall. Although summers are likely to become drier, rainfall events are predicted to become more intense: couple this with drier antecedent conditions in a clay catchment and the result could be much larger volumes of generated runoff and much faster catchment responses.

6. Applications

The results from the studied scenarios provide different information about the propagation and characteristics (extent and depth) of flooding across the River Cam floodplain at Hinxton, which

could have potentially changed the planners' location and orientation of the research centre where slightly more extensive and deeper flooding is shown to occur under the Fut-High scenario (Figure 5).

This research shows that when climate change impacts on rainfall–runoff modelling are combined with modelling the likely changes to the physical characteristics of a river catchment in the 2080s, the current 20% increase in flow as ascribed by PPS25 (DCLG, 2006) may not fully characterise a catchment's response at a particular location to a design flood event.

For developers, such an approach may provide more information that may better enable adjustments to the design of new developments to ensure their resistance and resilience to the uncertainties of future flooding dynamics.

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Appendix: Comparison of UKCP09 and PPS25 climate change information

UKCP09 climatic changes are compared with PPS25 climate change perturbation factors in Table 5. Where UKCIP02 values are used they are referenced. Low, mid and high estimates refer to the 95% (unlikely to be less), 50% and 5% (unlikely to be higher) probabilistic results from UKCP09 (Murphy *et al.*, 2009). Where ranges are presented for each estimate, the range represents maximum and minimum values from the spatially heterogeneous data.

Climate change factor	PPS25 weighting	UKCP09 projection	
Mean rainfall change	Not reported	2080s:	Little change (mid estimate) Up to –16% (low estimate) Up to 14% (high estimate) Not directly reported
Mean rainfall intensity change	Present–2055: +10% (peak intensity) 2055–2085: +20% (peak intensity) 2085–2115: +30% (peak intensity)		
River flow change	Present–2115: +20% (peak flow)		Not directly reported but can be calculated from other reported variables (rainfall, humidity, wind speed, temperature etc.)
Winter rainfall change	Not directly reported	2080s:	+2 to +30% (mid estimate) –11 to +9% (low estimate) +9% to +70% (high estimate)
Winter rainfall intensity	Not directly reported (use mean values with other methods, e.g. ReFH)	2080s (wettest winter day):	0 to +25% (mid estimate) –12 to +7% (low estimate) +13 to +56% (high estimate)
Winter river flow change	Not directly reported (accounted for in other methods, e.g. ReFH)		Not directly reported but can be calculated from other reported projections (rainfall, humidity, wind speed, temperature etc.)
Winter evapotranspiration change	Not directly included (use mean values with other methods, e.g. ReFH)		Not directly reported but can be calculated from other reported projections (humidity, temperature, wind speed etc.)
Winter soil moisture change	Not included.	2080s (UKCIP02):	0% (mid estimate) –10% (low estimate) +5% (high estimate)
Summer rainfall change	Not included (accounted for in other methods, e.g. ReFH)	2080s:	–40 to 0% (mid estimate) –65 to –6% (low estimate) –8 to +10% (high estimate)

Table 5. Comparison of UKCP09 climatic changes with PPS25 climate change perturbation factors (continued on next page)

Climate change factor	PPS25 weighting	UKCP09 projection	
Summer rainfall intensity change	Not directly reported (use mean values with other methods, e.g. ReFH)	2080s:	–12 to +12% (mid estimate) –38 to –9% (low estimate) –1 to +51% (high estimate)
Summer river flow change	Not directly reported (use mean values with other methods, e.g. ReFH)		Not directly reported but can be calculated from other reported projections (rainfall, humidity, wind speed, temperature etc.)
Summer evapotranspiration change	Not directly included (use mean values with other methods, e.g. ReFH)		Not directly reported but can be calculated from other reported projections (humidity, temperature, wind speed etc.)
Summer soil moisture change	Not included	2080s (UKCIP02):	–30% (mid estimate) –20% (low estimate) –40% (high estimate)
Relative humidity	Not included	2080s:	–9% (mid estimate) –20% (low estimate) 0% (high estimate)
Wind speed	Not included	2050s Long-term trends:	0% (mid estimate) –15% (low estimate) +10% (high estimate)

Table 5. (continued)

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